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# DEVELOPING ARCHAEOMAGNETIC DATING IN THE BRITISH IRON AGE

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## **Abstract**

### Developing archaeomagnetic dating in the British Iron Age

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Archaeomagnetism is an area of research that utilises the magnetic properties of archaeological materials to date past human activity. This research aimed to use the evidence of past geomagnetism, as recorded by archaeological and geological materials, to identify and characterise short timescale changes in the Earth's magnetic field. This contribution to the discipline focused on the first millennium BC, as there is evidence that during this time the Earth's magnetic field experienced rapid changes in direction. This work focused on an established weakness in archaeomagnetic studies, i.e. the application of archaeological information to assign a date range to the magnetic directions. The date ranges for 232 magnetic directions from 98 Iron Age sites were reviewed and a programme of fieldwork produced 25 new magnetic directions from 11 Iron Age sites across Britain. The approach developed in this thesis has made significant improvements to the data examined, which represent the prehistoric section of the British secular variation curve (SVC). These data have been incorporated into the British archaeomagnetic dataset that now comprises over 1000 magnetic directions and will be used to generate future British SVCs. The potential of the near continuous records of geomagnetic secular variation from British lake sediment sequences to SVCs was explored. This showed that these sediments have recorded the relative changes in the Earth's magnetic field but the dating and method of constructing the British master curve requires revision. As SVCs are predominately used as calibration curves for archaeomagnetic dating, this work provides a foundation for a revised and extended British SVC. This revision would be to the mutual benefit of studies in archaeology and archaeomagnetism, as the latter could potentially enable high-resolution dating of Iron Age material, providing a viable alternative to radiocarbon dating.

**Keywords:** archaeomagnetism, dating, Iron Age, secular variation, calibration curve, Britain, first millennium BC, geomagnetic

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## Glossary

**$\alpha_{95}$ :** a measure of dispersion on the surface of a sphere, specifically how scattered the individual vectors used to calculate a mean vector are using Fisher statistics.

**Anisotropy energy:** is energy that is directionally specific. The energy required to deflect magnetic domains within the crystal structure of a magnetic mineral from their spontaneous positions in the lowest energy state for these atoms (the “easy” direction) to a higher energy state (“hard” directions).

**Archaeomagnetism:** the study of past secular variation in the EMF using archives of remanence – produced from natural or anthropogenic sources or processes over time scales of less than 1 million years. This field of study does not include inversions, reversals or excursions.

**Bacterio remanent magnetisation (BRM):** the remanence acquired due to the presence of bacterial magnetofossils within the sediment, associated with sediment deposition or chemical changes in the sedimentary environment.

**Bauer plots:** a specific method of displaying archaeomagnetic data, where declination is plotted on the x axis (abscissa) and inclination on the y axis (ordinate).

**Bayesian approach:** emphasises that the interpretation of any dataset is conditional on the available information and on an individual’s understanding of the available information at that time.

**Bayesian statistics:** uses probability to measure the strength of a particular hypothesis being true given the available information and current understanding of that information.

**Biogenic magnetite:** is produced through the reduction of ferric iron by both biologically induced (extracellular) and biologically controlled (intracellular) processes. With few exceptions, all are ultra-fine-grained, single-domain magnetite.

**Calibrated radiocarbon date (CRD):** radiocarbon determinations are calculated on the assumption that the concentration of atmospheric radiocarbon has remained constant. This is incorrect so requires calibration to provide a date in calendar years (BC/AD).

**Cartesian coordinates** are rectilinear two-dimensional or three-dimensional coordinates. The three axes of three-dimensional Cartesian co-ordinates conventionally denoted the x-, y-, and z-axes are chosen to be linear and mutually perpendicular. In three dimensions, the co-ordinates, x, y and z may lie anywhere in the interval  $-\infty$  to  $\infty$ .

**Characteristic remanent magnetisation (ChRM):** used to calculate the mean vector and represents the most stable magnetic signal identified and isolated during laboratory processing of samples.

**Chemical remanent magnetisation (CRM):** the remanence acquired by crystal growth within a magnetic field at a constant temperature.

**Declination (Dec or D):** a component of the EMF. It is defined as the angle between magnetic north and geographic north. Together with inclination describes the magnetic vector (direction).

**Dendrochronology:** a scientific method of dating based on the analysis of patterns of tree rings.

**Coercivity:** the intensity of the magnetic field needed to reduce the magnetisation of a ferromagnetic material to zero after it has reached saturation. It provides a measure of the resistance of a ferromagnetic material to becoming demagnetised.

**Detrital remanent magnetisation (DRM):** the remanence acquired by sediments primarily deposited in water or air. This is a general term for the combination of physical alignment processes represented by DDRM and PDRM.

**Depositional detrital remanent magnetisation (DDRM):** the remanence acquired as detrital magnetic particles become aligned with the EMF in the water column as they fall out of suspension.

**Earth's magnetic field (EMF) also called the geomagnetic field:** this is produced internally due to magnetohydrodynamic forces created by the movement of the fluid outer core of the Earth's interior.

**Event:** a specific moment in time of special interest that can be directly identified in the archaeological or stratigraphic record.

**Feature:** a volume of material which can be considered to have been magnetised at the same point in time. Often forms an identifiable archaeological unit or feature such as a hearth or kiln structure.

**Gaussian statistics:** are based around central limit theorem, which provides a partial explanation for real-world observations which tend to be approximately normally distribution. This considered the most "basic" continuous probability distribution and as it is commonly encountered in practice, it is used throughout statistics, natural sciences, and social sciences as a simple model for complex phenomena.

**Hallstatt culture:** the predominant Central European culture from the 8th to 6th centuries BC (European Early Iron Age), developing out of the Urnfield culture of the 12th century BC (Late Bronze Age) and followed in much of Central Europe by the La Tène culture. The style and decoration of this culture are very distinctive and artefacts made in this style are widespread across Europe.

**Holocene:** a geological epoch which began approximately 12, 000 years ago, and represents the time since the end of the last major glacial epoch, or "ice age." Since then, there have been small-scale climate shifts - notably the "Little Ice Age"

between about AD1200-1700 but in general, the Holocene has been a relatively warm period.

**Inclination (Inc or I):** a component of the EMF. It is defined as the angle between the magnetic vector and the horizontal plane. Together with declination describes the magnetic vector (direction).

**In situ:** presumed not to have been displaced, deformed or tilted since the last firing or heating event.

**Isochrones:** spatially distant points that have the same numerical value of some variable, typically in archaeology this variable is time.

**k:** a measure of precision in Fisherian statistics.

**La Tène culture:** a late Iron Age culture (from 450 BC to the Roman conquest in the 1<sup>st</sup> century BC) in central Europe. It developed out of the early Iron Age Hallstatt culture without any definite cultural break, under the impetus of considerable Mediterranean influence and appears across Europe.

**Lithosphere:** is the rigid, outermost shell of a rocky planet. It comprises the crust and the portion of the upper mantle that behaves elastically on time scales of thousands of years or greater. The lithosphere is broken into tectonic plates and the uppermost part of the lithosphere that chemically reacts to the atmosphere, hydrosphere and biosphere through the soil forming process is called the pedosphere.

**Magnetic field:** a phenomenon produced by the movement of an electric charge, for example the movement of electrons around a nucleus.

**Magnetotactic bacteria:** a class of bacteria discovered in the 1960s, which orient along the magnetic field lines of the EMF. To perform this task, these bacteria have organelles called magnetosomes that contain magnetic crystals.

**Master curve:** a specific approach to combining several stratigraphic records. One sequence is selected as the master and the other sequences are matched individually to it but not each other.

**Median destructive field (MDF):** the strength of magnetisation necessary to remove half of the original remanent magnetisation present in a specimen or samples. It provides an indication of the dominant remanence carrying magnetic minerals present.

**Natural remanent magnetisation (NRM):** a generic term given to the initial magnetisation of any sample before processing to avoid any assumptions about the currently unknown origin of remanence, as the method by which magnetisation was obtained depends on the geological history of the sample.

**Optically stimulated luminescence (OSL):** a method for measuring doses from ionizing radiation and makes use of electrons trapped between the valence and electron band in the crystalline structure of certain types of matter. In

archaeology it is used to date minerals, like quartz and feldspars. Events that can be dated using OSL dating are for example last exposure to sunlight or when applied to dating ceramics, the dated event is the time of last heating to high temperature (in excess of 400 °C).

**Palaeolimnology:** the study of the history and development of freshwater ecosystems, especially lakes.

**Palaeomagnetism:** the study of the record of the EMF in rocks and deals with time scales over 1 million years and so includes magnetic inversions, reversals and excursions.

**Paramagnetism:** a form of magnetism that occurs only in the presence of an externally applied magnetic field.

**Post-depositional chemical remanent magnetisation (PCRM):** remanence acquired during the formation of a new magnetic material, e.g. the reduction of haematite to magnetite in organic rich deposits.

**Post-depositional detrital remanent magnetisation (PDRM):** remanence acquired by the sediment as it consolidates after deposition.

**Posterior density estimate (PDE):** the primary result of a Bayesian analysis of continuous data. It includes a representation of “how much belief do I attach to the possible values of the unknown parameters after observing the data?” A relatively large value means that it is relatively likely and a relatively small value means that it is relatively unlikely.

**Quaternary:** the most recent geological period covering the last 2.6 million years of the Earth’s history and represents the time during which recognisable humans existed.

**Radiocarbon determination:** this is the laboratory measurement of a time-independent level of  $^{14}\text{C}$  activity in the past. The hypothetical level of  $^{14}\text{C}$  activity is equal to the activity of an absolute international radiocarbon standard, so is quoted as before present (BP) where present is taken to be 1950 and for several reasons (Bowman 1990; Bronk Ramsey 2008a) and requires calibration.

**Reference curve, also see secular variation curve (SVC):** a record of past changes in the EMF built up from numerous discrete measurements recovered from historical observations or archaeological material. It represents current understanding of the past behaviour of the geomagnetic field over a given area.

**Remanence:** the ability of magnetic minerals to retain a magnetic direction in the absence of an applied field.

**RenCurve:** a piece of software developed at l’Université de Rennes, France that will produce secular variation curves from archaeomagnetic datasets.

**Sample:** an orientated volume of material collected from an archaeological feature.



**Secular variation (SV):** the variation of the geomagnetic field at the Earth's surface over time scales of less than a million years and arises from rearrangements of fluid motion in the Earth's core over years and decades.

**Secular variation curve (SVC):** a reconstruction of the behaviour of the past geomagnetic field. Typically it is estimated from a series of discrete magnetic directions obtained from archaeological material. The principle assumption is that materials synchronous in time over a region of 500km should have similar geomagnetic characteristics and this leads to regional "reference curves".

**Specimen:** a smaller unit of material taken from a sample.

**Stability index (SI):** a formula for measuring the stability of a remanent magnetic signal. It facilitates objective comparisons of samples from the sample feature to indicate the optimum laboratory treatment required to isolate the most stable component of remanence.

**Stratigraphy:** in archaeology, soil stratigraphy is used to better understand the processes that form and protect archaeological sites. It is based on the law of superposition "*Sedimentary layers are deposited in a time sequence, with the oldest on the bottom and the youngest on the top*" so can help to date finds or features from each context, as they can be placed in sequence and the dates interpolated. Phases of activity can also often be seen through stratigraphy, especially when a trench or feature is viewed in section (profile). As pits and other features can be dug down into earlier levels, not all material at the same absolute depth is necessarily of the same age.

**Tephra:** a generic name for the fragmented material produced by a volcanic eruption regardless of composition, fragment size or emplacement mechanism.

**Tephrochronology:** the use of tephra layers, which bear their own unique chemistry and character, as temporal marker horizons in archaeological and geological sites. Discrete layers of volcanic ash from a single eruption are used to create a chronological framework in which archaeological records can be placed. This method assumes that each volcanic event produces a unique chemical signature allowing it to be identified across the area affected by fallout.

**Thermal remanent magnetisation (TRM):** the remanence acquired by cooling from the Curie point (for most archaeological materials, temperatures over 580°C) in a magnetic field.

**Thermoluminescence (TL):** a method of dating a material containing crystalline minerals by determining the accumulated radiation dose of the time elapsed since the material was either heated or exposed to sunlight. Part of the same family of techniques are OSL but as the material is heated during measurements, a weak light signal, the thermoluminescence, proportional to the radiation dose is produced.

**Viscous remanent magnetisation (VRM):** the remanence acquired by the presence of magnetic domains with low relaxation times within the mineral matrix.

# 1. Introduction

“A strong limitation on what can be achieved with currently available palaeomagnetic records is the poor quality of most of the associated chronologies” (Barton 1982: 208)

“Time present and time past are both perhaps present in time future, and time future contained in time past. If all time is eternally present all time is unredeemable.”

T.S. Eliot “The Four Quartets. No 1: Burnt Norton” 1935

## 1.1 Research outline

The primary aim of this research is to use studies of the geomagnetic field, as recorded by archaeological and geological materials, to identify and characterise short timescale changes in the Earth’s magnetic field (EMF). The geomagnetic field displays a wide spectrum of time variations from hourly (Martini & Mursula 2008) to millions of years (Hatakeyama & Kono 2002), so in this context ‘short’ refers to variations occurring over several tens of years. This area of research is archaeomagnetism and this contribution to the discipline will focus on the first millennium BC, specifically the archaeology from the Iron Age period of British prehistory. Conventionally, the British Iron Age occupies the period between 700BC and AD43 (Hill 1995b: 47) and there is evidence from across Europe that the EMF experienced rapid changes in its direction during this time (Stockhausen 1998; Frank et al. 2002; Ojala & Saarinen 2002; Snowball & Sandgren 2002; Ojala & Tiljander 2003; Nourgaliev et al. 2005; Snowball et al. 2007). Together these findings suggests that archaeomagnetism could potentially enable high-resolution dating of British Iron Age archaeology and thus provide a viable alternative to radiocarbon dating, particularly given the perceived limitations of the latter for the British Iron Age (Haselgrove et al. 2001). This thesis will review all the prehistoric archaeomagnetic data available, collect new data for the target period and put forward a potential methodology for deriving date ranges for archaeomagnetic data from the associated archaeological information.

## 1.2 Scheme of research

Archaeomagnetism is the study of the changes in the geomagnetic field during the Holocene period. It predominately focuses on the analysis of the remanent magnetisation archived through the action of heat on materials recovered from archaeological sites; therefore, archaeomagnetism covers the most recent past, at millennial and centennial timescales. It is based on two physical phenomena: that the Earth has a geomagnetic field which changes over time and that under certain conditions naturally occurring minerals can record the ambient geomagnetic field (Linford 2006: 3). One of these conditions is the action of heat on clay, making archaeomagnetism ideally suited to date anthropogenic activity directly, via pyrotechnological processes, for example, hearths, kilns, ovens, furnaces or hypocausts. In this research pyrotechnology is taken to imply the intentional use and/or control of fire, so will include campfires as well as more formalised or industrial uses of fire. All dating techniques that exploit naturally occurring phenomena encounter difficulties when attempting to relate the event the phenomenon is dating to the event of archaeological interest, with radiocarbon dating presenting an excellent example of this conundrum (Bronk Ramsey 2008a). However, with archaeomagnetism these two events have a clear relationship, as this method dates the last time a feature cooled down and so relates to the end of use of that feature; thus, archaeomagnetism can provide a terminus ante quem for the structure that contains it. As with radiocarbon dating, archaeomagnetism also requires a calibration curve, which in this case traces the pattern of changes in the geomagnetic field back through time. This thesis forms a contribution to the on-going research to refine current understanding of the secular variation experienced by the geomagnetic field. In order to redefine understanding of the nature of past changes in the geomagnetic field during the first millennium BC, four objectives were set.

**Objective 1: an evaluation of published archaeomagnetic studies on Iron Age archaeology in Britain, with particular focus on 800BC - AD100 to provide a revised dataset for an updated British secular variation curve (SVC).**

Archaeomagnetic dating is essentially a derivative dating method, matching regionally specific patterns of secular variation in the geomagnetic field. Since the potential application of archaeomagnetic studies was first recognised (Thellier 1938), several different approaches to estimating the past secular variations of the EMF have been proposed (Aitken 1958; Clark et al. 1988; Sternberg & McGuire 1990b; Wolfman 1990b; Batt 1997; Le Goff et al. 2002; Lanos 2004; section 7.3), but all regional patterns have to be built up from individual magnetic measurements of numerous archaeological resources. The date for each magnetic phenomenon has to be established by other chronometric methods, typically historical records, typology, radiocarbon dating or dendrochronology, as the secular variation pattern of geomagnetism is not predictable (Batt 1997). Therefore, in practice, it is necessary to assign a date range to each discrete magnetic direction in order to construct a regional calibration curve, which in archaeomagnetic studies is called a secular variation curve or SVC. The chronological placement afforded to the majority of the magnetic direction determinations that comprise the current British SVC curve are based on the evidence recovered from the archaeological record. The main limitation of this method is that most points that relate to the first millennium BC have just been described as “Iron Age”, and so are ascribed the generic date range 700BC-43AD. In this study, it was decided to examine all magnetic data that fell within the period 800BC-AD100 (chapter 4), so that there was some overlap beyond the traditional definition of the Iron Age period in Britain, thereby ensuring that all potential data were considered. During the past fifty years since British archaeomagnetic studies began (Sternberg 2008), there have been significant changes in the theory and practice of archaeology, particularly Iron Age archaeology (Haselgrove et al. 2001; Haselgrove & Moore 2007; Haselgrove & Pope 2007b; chapter 2). It is suggested that a re-evaluation of the dates allocated to magnetic directions in the published British dataset may enable the age range associated with each data point for the target period to be reduced to less than ~750 years.

**Objective 2: the collation of currently unpublished magnetic data and allocating a chronological assignment to each magnetic direction, so that it can be added to the British and global archaeomagnetic dataset and used to produce an updated British SVC.**

In addition to reviewing the existing dataset, it was also deemed pertinent to collate magnetic data produced by other laboratories. This approach would involve contacting other researchers and surveying the grey literature for any data previously not included in the British database. With these new data, it would be necessary to identify the associated date range for each magnetic direction (section 4.2). The new data would provide an opportunity to apply the lessons learnt from objective 1 to be put into practice, and to assess the merits of the methodology to allocate date ranges from the associated archaeological evidence as available from modern excavations.

**Objective 3: the collection of new magnetic data that will be incorporated into the British and global archaeomagnetic databases.**

The Iron Age period of British prehistory is characterised by an increased use of pyrotechnology, reflected in the archaeological record by a distinctive architectural form that relates to the manufacture of ceramics and metal objects. Typically, these architectural features were constructed from clay and, therefore, are ideally suited for archaeomagnetic dating as they are capable of recording the contemporary geomagnetic field through a mechanism known as thermoremanent magnetisation (TRM, section 3.6). Furthermore, in some areas of Britain it appears that hearths became more formalised in the Iron Age period (Armit 2002), a shift of focus that has several implications for understanding past social organisations. For the purposes of this research, it means that the Iron Age provides an excellent opportunity to explore the potential of archaeomagnetism as a dating method. Archaeomagnetism is frequently overlooked by archaeologists, so a sampling campaign was devised to promote this technique and to collect new data (chapter 5). This included a programme of fieldwork to collect material for processing in the archaeomagnetic laboratory at the University of Bradford.

#### **Objective 4: an investigation into the incorporation of magnetic data from British lake sedimentary sequences into the British archaeomagnetic SVC.**

There are processes other than the action of heat that can capture the changes in the Earth's geomagnetic field over time. For the British Holocene epoch, lake sediments can provide a near continuous record of secular variation over the last 12, 000 years. These sediments can record changes in the geomagnetic field through a mechanism called depositional remanent magnetisation (DRM) (Collinson 1965; Tauxe et al. 2006; section 3.7). As SVCs have to be built up using many individual data points, the continuous sequence of geomagnetic secular variation recorded in lake sediment sequences could potentially provide a useful addition. The feasibility of incorporating data from British lake sediments will be assessed (chapter 6) as this dataset covers the entire Holocene, meaning that all archaeological periods from the Mesolithic onwards could be dated via archaeomagnetism. However, this archive of magnetic data is problematic, and although it was included in a previous incarnation of the British SVC (Clark et al. 1988), the most recent SVC revision excluded it (Zananiri et al. 2007). The approach taken in this research is to focus on the quality of the available data and particularly the application of dating evidence to the archive of geomagnetic data in sediment sequences from British lakes.

### **1.3 Research rationale**

This work should form a valuable contribution to current research in the field of archaeomagnetic dating, particularly as other researchers are now beginning to appreciate the restrictions of archaeological data (Kovacheva et al. 2009) and the archaeological process (Schnepp & Lanos 2005). It is hoped that the proposals made in this thesis may help future workers to make the most of the information available from the archaeological record. Ultimately, it is envisaged that the data presented in this thesis will augment both the ability of archaeologists to define the chronology of the British Iron Age, and palaeomagnetists to understand the nature of past changes in the geomagnetic field. Recent palaeo and

archaeomagnetic studies have focused on exploring the potential of a modelling methodology to develop regional, or global, models of the geomagnetic field (Korte & Constable 2008; Pavón-Carrasco et al. 2008, 2009; Lodge & Holme 2009). This thesis will argue that these studies have under-estimated a fundamental aspect of constructing mathematical models, i.e. that any model is only as reliable as the data used to create it. In this case, it would appear that whilst the poor quality of the archaeological date ranges is acknowledged, this obstacle remains as the statistical modelling packages available twenty-five years ago were capable of constructing “a smooth curve from random numbers” (Clark 1983: 249). The availability of more sophisticated programmes means that it is now imperative that the data used are reliable, and that the associated errors are defined and understood. These improvements in computing also mean that it should now be possible to deal with complex datasets, as long as the issues are fully quantified, because, in practice, the degree of smoothing applied is of more importance than the method of smoothing (Clark 1983). Therefore, it is suggested that improving the precision and developing a method of assessing the reliability of the data should lead to significant improvements in understanding the nature of past geomagnetic secular variation.

Any calibration curve or SVC is essentially a mathematical model based on current understanding of the phenomena under study. If its principal application is to date archaeological artefacts then high quality data are required, so that a high resolution curve can be generated that can potentially identify changes occurring over timescales relevant to human lifetimes. For the specific case of archaeomagnetic SVCs, that form the focus of this research, there are two components to consider: the magnetic data and the associated dating information. It has already been recommended (Aitken 1990: 243; Bucur 1994) that to achieve a reliable archaeomagnetic calibration curve it is necessary that there are at least 5 well dated points per century; the error ranges for the magnetic directions should be under 5° for archaeomagnetic dating and the error ranges for the dates should be  $\pm 100$  years or less. However, much of the current British reference curve dataset

does not fit the criteria relating to points per century or restrictions on the date error ranges. The latter problem has been recognised for some time (for example, Barton 1982; Bucur 1994; Márton 2003; Donadini et al. 2009). Although recent modelling software packages (Lanos et al. 1999; 2005) have been able to make some concessions for the quality of the magnetic data, by weighting the analysis towards the reliable magnetic data, until now no such treatment has been allowed for the dating evidence. This limitation means that the prehistoric section of the current British SVC is poorly defined (Pavón-Carrasco et al. 2011). Therefore, this research will focus on the problem with dating. It appears that the main problem is related to expectations of the level of precision required. This area of research began in palaeomagnetism, which focuses on geological timescales, where age errors of  $\pm 300$  years are considered to be a reasonable error margin; but, for archaeologists, this large error is entirely unacceptable. Fully addressing this problem will require a clearer understanding of the nature of archaeological evidence, how it is applied, its strengths and limitations and how to account for these in any statistical model of secular variation.

It is envisaged that the work presented in this thesis may eventually facilitate archaeological discussions of the chronological issues created by using diagnostic artefacts; in particular, how this limits the ability of archaeologists to identify social expression and identity on a regional or even national basis. Archaeological understanding and the expectations of the archaeological record change over time (Haselgrove 2009), but archaeomagnetism can provide a viable alternative to typology for dating and provide dates that are still intimately linked to the production of the artefact and their relationship to the archaeological record. Furthermore, archaeomagnetism may also indirectly assist the production of “artefact biographies” (Gosden & Marshall 1999). Although this concept is not new, it appears to be an area of increasing interest, as researchers are recognising and embracing the fact that many artefacts and even structures had long, multifaceted histories of use (Caple 2006; Herva 2010; MacGregor 2010).



## **1.4 Structure of the thesis**

There are two main theoretical branches to this thesis, and these are described with appropriate background material in chapters 2 and 3. Chapter 2 focuses on the origin of the associated archaeological estimates in the current British archaeomagnetic dataset and presents the argument that this can have a significant impact on the application of these data, particularly with respect to the construction of a SVC. The discussion in chapter 3 revolves around recognising the relationship between the natural phenomenon that captures and archives the contemporary geomagnetic field and the event of archaeological interest. Together, these two aspects are essential to the central principle of archaeomagnetic dating, the SVC. This thesis argues that it is essential that the relationship between the recorded geomagnetic direction and the event that recorded this direction is clearly defined, so that the available archaeological dating evidence can be applied critically and consistently. Making the theoretical basis clear is considered necessary, as it underpins the methodology presented in chapters 4 and 6. The method and results arising from considering archaeological material is presented in chapter 4. Chapter 5 describes the programme of fieldwork that was undertaken and presents the results from the laboratory work undertaken. Subtle but significant differences were encountered with the magnetic data from lake sediments, so they were dealt with separately in chapter 6. Chapter 7 discusses how SVCs are constructed and describes how the alterations made to the current dataset will benefit future British SVCs. Finally, chapter 8 provides a summary of the most salient findings of this research and outlines some avenues for further work. There is also a glossary of terms utilised in this thesis and four appendices (on the accompanying CD). Appendix 1 contains all of the data examined during this research. Appendix 2 comprises a gazetteer of the 98 sites examined. Appendix 3 provides a laboratory report for each of the 11 sites visited for fieldwork. The updated British archaeomagnetic database (as an Access database) is appendix 4.

## **2. Previous developments in the research of Iron Age archaeology and archaeomagnetic dating in Britain**

“Errors using inadequate data are much less than using no data at all.”

Charles Babbage (1791-1871)

### **2.1 Introduction**

As the focus of this research is on changes in the geomagnetic field during the first millennium BC, it will include archaeology from predominately Iron Age sites located across Britain. Therefore, it is useful to demonstrate something of the range of archaeological evidence that has been recovered from the British Isles in this period. The archaeology outlined in this section is considered diagnostic of the British Iron Age, although not all of the attributes mentioned are contemporaneous and did not happen everywhere in Britain. Essentially, the concept of an Iron Age, like other chronological periods, is a disciplinary invention, but it has been dogged by the implicit assumption that it is a self-contained unit for study (Collis 1977b; Champion & Megaw 1985; Champion & Collis 1996). Other researchers place emphasis on the impression of continuity from the Bronze Age and advocate that nothing is especially extraordinary about Britain from the geographical regions surrounding it (Sørensen & Thomas 1989; Kristiansen & Jensen 1994; Davis et al. 2008b). Whilst subtle distinctions in the definitions of terminology form part of academic discussion, in the case of Iron Age studies it appears to have limited our understanding, particularly with reference to the time frames in which archaeological developments took place. This is perhaps partly due to the false sense of continuity of our modern society with the Iron Age (Champion 1987), which has tended to dictate, or at least contributed to, the way that the considerable corpus of information on the Iron Age should be interpreted. This chapter is divided into two parts. The first will attempt to provide an abridged background to British Iron Age archaeology and highlight some of the chronological issues pertinent to the first millennium BC. The second half will deal with studies on

the geomagnetic field, via a condensed overview of the development of archaeomagnetic studies in Britain and their application to archaeology.

## **2.2 The chronological framework of the British Iron Age**

The British Iron Age is marked by the scale of regional variation present in the available archaeological evidence, leading to the development of a series of regional chronologies. Yet there is a general consensus that, throughout Britain, the commencement of the Iron Age is coeval with the beginning of Hallstatt C in Europe, so around 800BC (Haselgrove & Pope 2007a). This statement has been subject to much debate over the past decade (see Needham 2007 for a summary), with some authors arguing that it took place earlier, around 1500BC (Collis 1977a; Bradley 1998; Needham 2007). Otherwise, three sub divisions to the British Iron Age are recognized: early, middle and late. However, it is only when considering the end of the Iron Age period that the impact of the variation within each regional chronology becomes obvious. For example, in Wessex, the Roman invasion at AD43 is seen as the end of the Iron Age; conversely the Roman Empire is considered to have not had a significant impact on regions further north, resulting in a progressively longer chronology for northern areas. The current chronology is summarised in table 2.1 and the main arguments supporting it are presented below.

### **2.2.1 Early Iron Age**

It was around 800BC that settlements started to dominate the archaeological record (Bradley 1998: 158f), in contrast to the highly visible funerary landscape of the Bronze Age. Moreover, the early Iron Age in certain areas show much continuity with the Late Bronze Age in Britain (e.g. Champion 1994), particularly in continuity of settlement locations, pottery typologies and the deposition of metal objects into rivers and bogs (Barrett & Bradley 1980; Bradley & Gordon 1988; Hunter 1997). Whether due to low population densities or the nature of the archaeological evidence, the earlier Iron Age is more diffuse than later

periods. Specifically, the period between 800-300BC has “tended to be characterised more by what it lacks than what it comprises” (Haselgrove & Pope 2007a: 1), although it is possible that much early Iron Age material has been misidentified as later Bronze Age (Brudenell 2008).

Date	Western European chronology as applied to Britain (Champion <i>et al.</i> 1984; Haselgrove 1997)	Southern Britain (Collis 1977a)	Northern Britain/ Southern Scotland	Atlantic Scotland (Foster 1989)	Coins (Haselgrove 1996)
1000BC		Late Bronze Age/Earliest Iron Age	Late Bronze Age/Earliest Iron Age		
900BC					
800BC					
700BC	Hallstatt C	Early Iron Age	Early Iron Age	Early Iron Age	
600BC					
500BC	Hallstatt D1				
400BC	Hallstatt D2/3 La Tène Ia				
300BC	La Tène Ib	Middle Iron Age	Middle Iron Age	Middle Iron Age	
200BC	La Tène Ic				Period I, Phase 1 (mid ) Period I, Phase 2 (late)
100BC	La Tène II/III				Period 1, Phase 3 (early) Period 2, Phase 4 (80-60BC) Period 2, Phase 5 (60-50BC) Period 2, Phase 6 (50-40BC) Period 3, Phase 7 (20BC-AD10)
0					Period 3, Phase 8 (AD10-40)
AD100					Period 3, Phase 9 (AD30-45)
AD200					
AD300		Late Iron Age I			
AD400					
AD500		Late Iron Age II			
AD600					
AD700					
AD800					

Table 2.1: Summary of the chronological divisions that are currently applied to Iron Age studies in Britain which demonstrates the regional variations.

Others believe that significant changes can be identified around 800BC (Henderson 2007; Ralston & Ashmore 2007); namely changes in the focus for status, from display through metalwork to display through domestic architecture. This school of thought further interprets the increased visibility of field systems seen in southern Britain as due to a new focus on the ability to produce and store surplus food.

### **2.2.2 Middle Iron Age**

From 400-300BC many aspects of the archaeological record become more visible and some underlying trends can be discerned, including increased permanent woodland clearance, intensification of land use and expansion of settlement into more 'marginal' areas (Jones 1996). These are accompanied by the adoption of new technologies, for example, iron tipped ard ploughs, which would allow heavier soil to be tilled, and the rotary quern. New species were also incorporated including domesticated fowl, bread wheat and rye. Towards the end of the second century BC the introduction of coinage can be identified across southern England (Haselgrove 1996), then around 100BC there are more archaeologically visible developments, including the introduction of the fast potter's wheel and the consequent range of new pottery forms in the south (Hill 1995b). More recent work acknowledges that regional variation is a prominent and indispensable feature of the middle Iron Age period in Britain requiring consideration (Haselgrove et al. 2001), which has revealed the complex nature of indigenous farming practices and craft production (Hill 1995a).

### **2.2.3 Late Iron Age**

Regarding the end of the Iron Age period, in southern Britain it is seen as coinciding with the Roman invasion by Claudius in AD43. This is a hangover from the invasionist paradigm that predominated up to 1960 (for example see Frere 1958), but has been retained as part of the general chronological scheme, as it is a well-

established and convenient marker. Moving north, archaeological interpretations have not relied so heavily on classical texts, but retained AD43 as the beginning of the Roman Iron Age, which is seen to end around AD400. In central and northern England, this is the beginning of the Saxon period and in southern and north eastern Scotland the early medieval period. Atlantic Scotland has developed a unique chronology through an examination of the architectural development in the region. This has resulted in a much longer duration for the Iron Age in Scotland, continuing until the appearance of Norse material around AD800 (Foster 1989).

### **2.3 Overview of the archaeology of the British Iron Age**

It is not possible to synthesise the archaeology of the British Iron Age into a single, coherent, yet brief summary and still convey the range and depth of the material available. However, it should be feasible to provide an overview of the principal features identified archaeologically and for purposes of clarity and brevity this section is divided into settlement, economy and ritual. These divisions have been selected as they should be able to convey the degree of regional variation that is present in the archaeological evidence, and have proven useful categories when characterising a site as early, middle or late Iron Age. Several compilations of research into the Iron Age have been published (including Frere 1958; Collis 1977b; Champion & Megaw 1985; Bowden et al. 1989; Sørensen & Thomas 1989; Collis 1994; Kristiansen & Jensen 1994; Hill & Cumberpatch 1995; Champion & Collis 1996; Dungworth 1997; Gwilt & Haselgrove 1997; Collis 2001; Ballin Smith & Banks 2002; Dockrill et al. 2006; Haselgrove & Moore 2007; Haselgrove & Pope 2007b) and due to the geographical and temporal scope of this overview, one thousand years of British prehistory, it has been necessary to base much of the following commentary on these sources.

#### **2.3.1 Settlement**

Throughout the Iron Age, across the British Isles, the dominant settlement form appears to have been the household unit, with some village-sized

conglomerations (Hill 1995b). The specifics of these structures varied over time and space, but to consider just the range of relevant examples there are D-shaped enclosures (Wessex), rectilinear settlements (Midlands), banjo-enclosures (Hampshire, Oxfordshire), court-yard houses (Wales, Cornwall), wheelhouses (Atlantic Scotland) and crannogs (lakeside dwellings). Hillforts had been considered synonymous with the Iron Age and have been interpreted as the central places within pre-Roman Iron Age societies and often portrayed as proto-towns, central places for craft production, repositories of surplus foodstuffs and focus for trade (Cunliffe 1974). This model has now been widely rejected (Cunliffe 1985; Haselgrove 1986; Hill 1996) and instead it is argued that as they were built throughout the first millennium BC, in different areas, hillforts should be considered neither a coherent category of site nor ubiquitous (Hill 1995a; Collis 1996). In general, the archaeological record has been biased towards enclosed settlements as these are easier to identify, but in some areas they were not the norm (Harding 2004: 7); examples include the gravel terraces in Oxfordshire, the “Arras” culture in east Yorkshire and areas of the Scottish lowlands. More recent rescue excavations and infrastructure work have revealed several open Iron Age settlements in unexpected areas, for example in the Scottish borders (Pope 2003).

### **2.3.2 Economy**

There is increasing evidence that Iron Age societies practiced a mixed economy and that this regime generated surplus (Jones 1996; Dockrill & Batt 2004), where plants were exploited as food, fodder, fuel and building materials. Furthermore, there is evidence that their use for all of these was managed and controlled through conservation practices such as woodland management. Craft activities would have fitted in around food production; for example, iron-working, pottery production, basketry, spinning, weaving and exploitation of animal pelts and hides; but there is no evidence for permanent specialised production centres until after the Roman conquest (Hill 1995b; Morris 1996; Dockrill & Batt 2004). The Iron Age material culture is variable with some areas of Britain apparently aceramic, for example north-west England, and others displaying complex ceramic traditions,

for example Wessex. Other commodities were only exploited at specific locations, for example: shale, jet, salt, sea birds and pelts (Morris 1996). Whereas in certain areas there is evidence for the standardisation of craft production and industrialised processes (Bradley 1990: 172), it has recently been demonstrated that ironworking was being undertaken in Britain on a substantial scale at the beginning of the first millennium BC (Collard et al. 2006). Indeed, the existence of ceramic traditions indicates that there are agreed methods of shaping and decorating ceramic objects. There are other examples of orthodoxy including the production of iron in consistent units or “currency bars” (Hingley 1990); also, briquetage fragments from salt production suggest it was manufactured in standardised cakes (Healey 1999; Chowne et al. 2001; Lane & Morris 2001) and it has been suggested that grain storage pits were of a uniform size to store standard quantities of grain (Cunliffe 1984: 131).

### **2.3.3 Ritual**

Although demonstrating the “structured deposition” associated with rituals or the cosmological alignment of structures (Parker Pearson 1996) may be challenging, there is evidence that Iron Age societies did include some supernatural entity within their daily lives (Armit & Ginn 2007). A key feature of Iron Age societies is the incorporation of ritual activity into the domestic sphere, although the motivation behind this appears to have differed across Britain. In southern Britain, the presence of human remains in the grain pits at Danebury is suggested to be related to ensuring the fertility of the land (Bradley 1991). By comparison, the presence of human skulls in Hebridean wheelhouses and other sites in Atlantic Scotland is believed to be a form of ancestor worship and to show some continuity of settlement (Mulville et al. 2003; Armit & Ginn 2007; Tucker 2010). Wet places, for example, springs, bogs, rivers and lakes, also held a ritual significance (Coles & Coles 1989: 191). In Scotland, south-west England and the Thames basin (Wait 1985), water contexts were the focus for hoarding and the deposition of metal objects, as part of a longer tradition stretching back through the Bronze Age (Barrett & Bradley 1980; Hunter 1997). There are few examples of formalised



inhumations, in the modern sense, until the later Iron Age with the spectacular exception of the “Arras Culture” of east Yorkshire; these were La Tène style inhumations under square barrows and probably date to around 450BC (Stead 1979).

## **2.4 Dating the British Iron Age**

It appears that archaeologists are now embracing the diversity expressed in the archaeological record and fully accept that the Iron Age is not a single entity, but that this is a challenge and not a problem (Davis et al. 2008a). Even so, British Iron Age studies are infused with typological assumptions, with many key dates for ceramic sequences derived through unsubstantiated links with European stylistic sequences (Hodson 1964). Although aware of the limitations of his approach, Cunliffe’s survey of Iron Age communities, now in its fourth edition (2005), has become the standard reference work on this area of British archaeology. Since it was first published (Cunliffe 1974) subsequent work on the British Iron Age has demonstrated the sheer diversity of the archaeological record (see Champion & Collis 1996; Gwilt & Haselgrove 1997; Haselgrove & Moore 2007; Haselgrove & Pope 2007b and references therein), which the current chronological framework (table 2.1), is ill-equipped to resolve. The main frameworks that have been used to develop this current chronology are pottery typology and metalwork from continental Europe, in addition to the application of radiocarbon dating, and each are briefly outlined below.

### **2.4.1 Pottery typology**

Since the 1930’s, the pre-Roman Iron Age in England has been divided into three periods based on pottery typology: “Early” ca. 700-450 BC, “Middle” ca. 450-100BC and “Late” ca. 100BC-AD43 (Collis 1977a). This has proven to be a particularly versatile framework and has received constant refinement since it was introduced. Unfortunately, there are three main limitations to this chronological framework. Firstly, and most importantly, the majority of Britain is virtually

aceramic for most of the Iron Age (Harding 2004: 8), meaning that its applicability is limited to those sites, predominately in the south, that produce ceramic assemblages, and so is not suitable to link these spatially distinct regions of Britain. There is the exception of Atlantic Scotland, which has a quite separate scheme for pottery typology (Armit 1991). Consequently, this framework has reinforced the perceived north-south divide, first proposed by Fox (1932), and served to further highlight regional differences rather than provide an unbiased chronology.

A second limitation lies in the origins of this framework, the culture historic approach that has been largely replaced since the 1960's (Trigger 1989: 242). This system carries the implicit assumption that each period represents a new wave of influence, whether external or internal. In order to support more sophisticated archaeological investigations, the Iron Age requires a new method to provide chronological placement that is both directly related to the archaeology and entirely independent of it. The third limitation is that, as Hill suggests, pottery is an inappropriate vehicle for chronological assignments as it is primarily an indicator of ways of living and social identity (Hill 1995b). Where radiocarbon dating has been used it has shown that many ceramic forms were in use over a much longer period that was previously assumed, both from the preceding Bronze Age (Barrett 1980) and after the Roman conquest (Evans & Serjeantson 1988). Even so ceramics are routinely used to classify sites.

Archaeologists working at the beginning of the twentieth century created an artificial north-south divide following the commentaries on Britain made in classical texts, particularly by Caesar and Tacitus. Although the limitations of these sources are now more fully realised (Champion 1985), Cunliffe (1974) adopted a north-south division in the first attempt at a survey of British Iron Age archaeology. This served to perpetuate the notion that the north was isolated, both geographically and culturally, from the south of Britain during the Iron Age. Typically, a combination of the Western European and the Southern British chronology are

applied to all Iron Age sites south of Northumberland and the Scottish borders. The origin of these frameworks can be traced back to Hodson (1964) and Cunliffe (1974). However, the sequence of pottery typologies presented by Cunliffe (2005) primarily relate to the chalk downlands of southern Britain and so are inapplicable to most of the country (Collis 1977a; Harding 2004). In turn, the broad chronology and distribution of the style zones are ultimately based on collections of unstratified pottery (Cunliffe 1977). By comparison, for Atlantic Scotland the different nature of the archaeological record stimulated archaeologists to provide a separate chronology. In this region, the chronology has been founded on architectural developments that have been dated by radiocarbon determinations (Foster 1989).

#### **2.4.2 Continental metalwork**

The continental chronology is essentially based on types of metal work and when applied to British material provides the following divisions: “Hallstatt Britain” ca. 800-450BC and “La Tène Britain” ca. 450BC-AD100 (Haselgrove 1997: 52 figure 8.1; 2009: 131). The benefit of this framework is that it allows for contacts with Europe to be considered, throughout the Iron Age period, that are not catalysed by the Roman expansion, but it does include assumptions about mechanisms of exchange and the time involved for these artefacts to reach Britain. The British Isles has often been considered to be peripheral to and isolated from Europe; however, the English Channel and North Sea should not necessarily be considered barriers. A limitation with this approach is that metalwork was rarely deposited in settlement contexts, and there are exceedingly few Iron Age inhumations in Britain, making clear links between metal work chronologies and other chronologies more difficult to establish. Furthermore, several high status metal objects show evidence of repair, suggesting that they were in circulation for extended periods before deposition (Harding 2002). The manifestation of Hallstatt and La Tène metalwork as chronological indicators has been over rated in the past (Clarke 1971), but is still often the only guide available. The metalwork uncovered so far in Britain suggests that at least two significant shifts in society took place during the first millennium BC, i.e. during the first and seventh centuries BC. It is possible that these were a

series of smaller changes, where the cumulative effect only manifested itself much later. Meaning that the rate of change is key to understanding both the nature and causes of social development. This does not imply that the temporal placements assigned to categories of artefacts are incorrect, but instead that improvements can be made to the precision via the critical application of scientific methods of dating, as demonstrated for the Bronze Age with radiocarbon dating (Needham et al. 1997).

### **2.4.3 Radiocarbon dating**

Radiocarbon dating is the main scientific method of dating that is routinely applied to archaeology and, when incorporated with Bayesian analysis, provides a useful method of constructing chronological models. With respect to the British Iron Age, the application of radiocarbon dating has proven problematic due to the shape of the calibration curve during the first millennium BC (Reimer et al. 2009) (figure 2.1). It is widely believed that the application of radiocarbon dating to Iron Age material is ineffective, as it could only generate calibrated dates with large error ranges. This weakness has been blamed for hindering any significant progress towards identifying the rate of change in the archaeological record during this period for most of Britain. Although radiocarbon dating has been able to demonstrate the validity of the longer regional chronologies in southern and Atlantic Scotland (Haselgrove et al. 2001), examination of figure 2.1 shows that the features of the calibration curve that cause the largest errors (the plateau followed by a sharp rise and decline ~650-400BC) only affects the early Iron Age. Nevertheless, in order to make any progress it is necessary to find an alternative method of dating to remove some of the over reliance on radiocarbon dating; archaeomagnetism can provide that alternative. Once improvements are made to understanding of the secular variation of the geomagnetic field during the first millennium BC, it should be possible to investigate the factors that underpin chronological models of the British Iron Age.

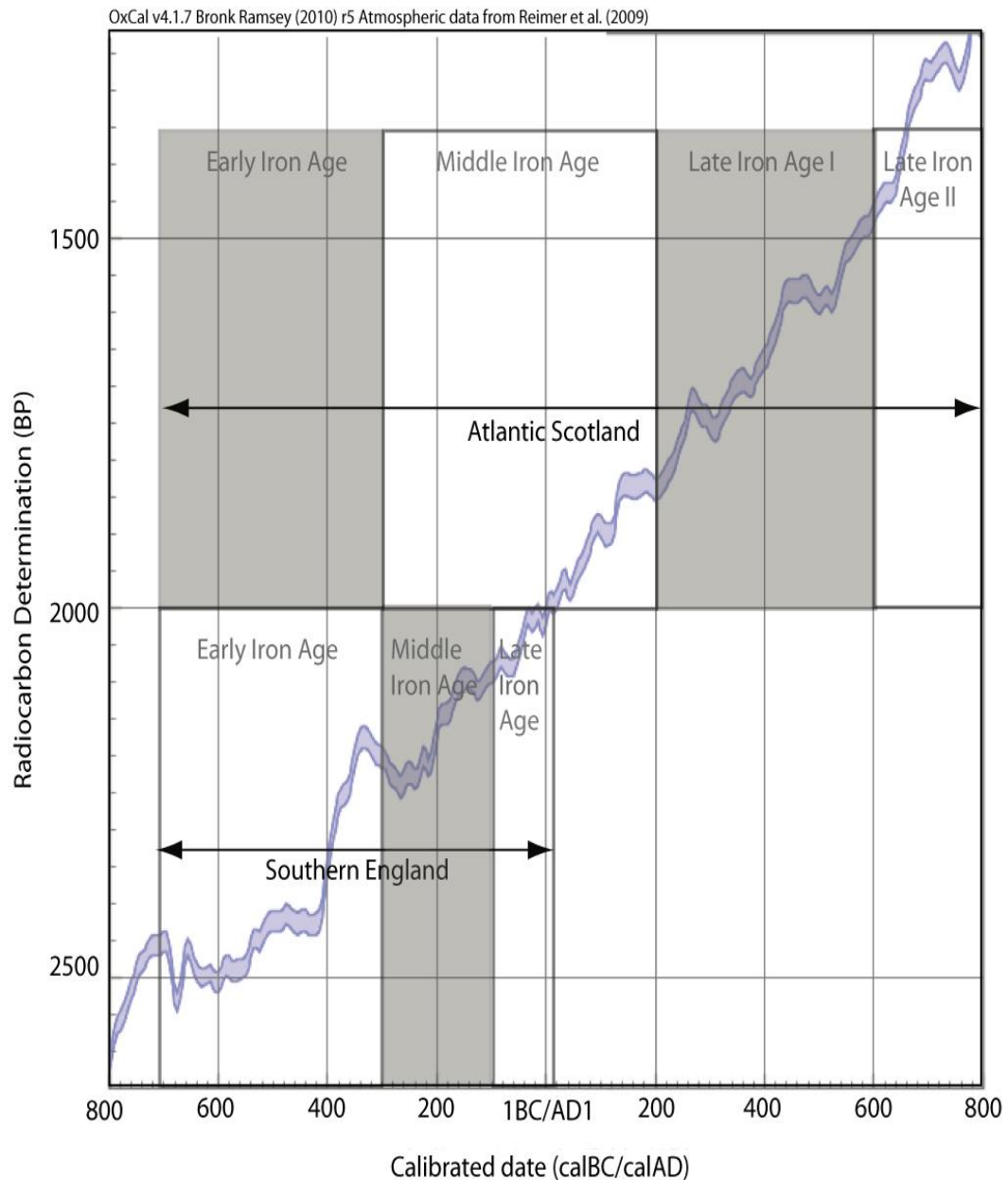


Figure 2.1: The radiocarbon calibration curve overlain with the sub divisions for the British Iron Age. The top subdivisions represent those applied to the archaeology of Atlantic Scotland, whereas those at the bottom apply to southern England; together these two extremes illustrate the full spectrum of age ranges applicable to British Iron Age archaeology.

Furthermore, as the archaeomagnetic dates have a direct relationship to the archaeology under investigation they can provide a date of abandonment for domestic structures, or a date of last use for kilns and furnaces, i.e. when specific ceramic typologies ceased to be produced but not necessarily went out of circulation.

## **2.5 A history of archaeomagnetic dating in Britain**

Archaeomagnetic dating is a relatively recent innovation, particularly since secular variation in the geomagnetic field was identified over three and half centuries ago (Gellibrand 1634) and that geomagnetism is considered to be one of the oldest sciences (Tarling 1983: 1). Tarling (1983: 1-8) provides a comprehensive review of the history of archaeomagnetism and the development of magnetic studies in general, with more recent discoveries briefly summarised by Linford (2006: 28). Although the potential of applying magnetic studies to both science and archaeology was only fully realised during the twentieth century, developments since then have progressed rapidly and work has been undertaken globally. Geomagnetism and magnetic properties have found use in a surprising number of applications, tracing environmental and cultural changes throughout the history of the Earth (see Evans & Heller 2003 for a summary), but here the focus will be on those working on archaeomagnetic dating in Britain and their output is illustrated in figure 2.2.

### **2.5.1 The early work**

In the first half of the twentieth century only a limited number of magnetic studies on archaeological artefacts had been performed in Britain. These exploratory investigations (Belshé 1957; Aitken 1960) lacked any cohesion or overall focus because they were investigating the potential of magnetism as an analytical tool. In particular, the ability of archaeological materials to record a remanent magnetisation and what these details could inform about the manufacturing conditions (Aitken 1958; Aitken & Harold 1959). Although the phenomenon of secular variation in the geomagnetic field was well established by the twentieth century (Tarling 1983: 4), it was not until the second half of the twentieth century that the concept of using archaeological material to produce a curve detailing the secular variation of the geomagnetic field in Britain, that extended beyond the historical records, was fully acknowledged.

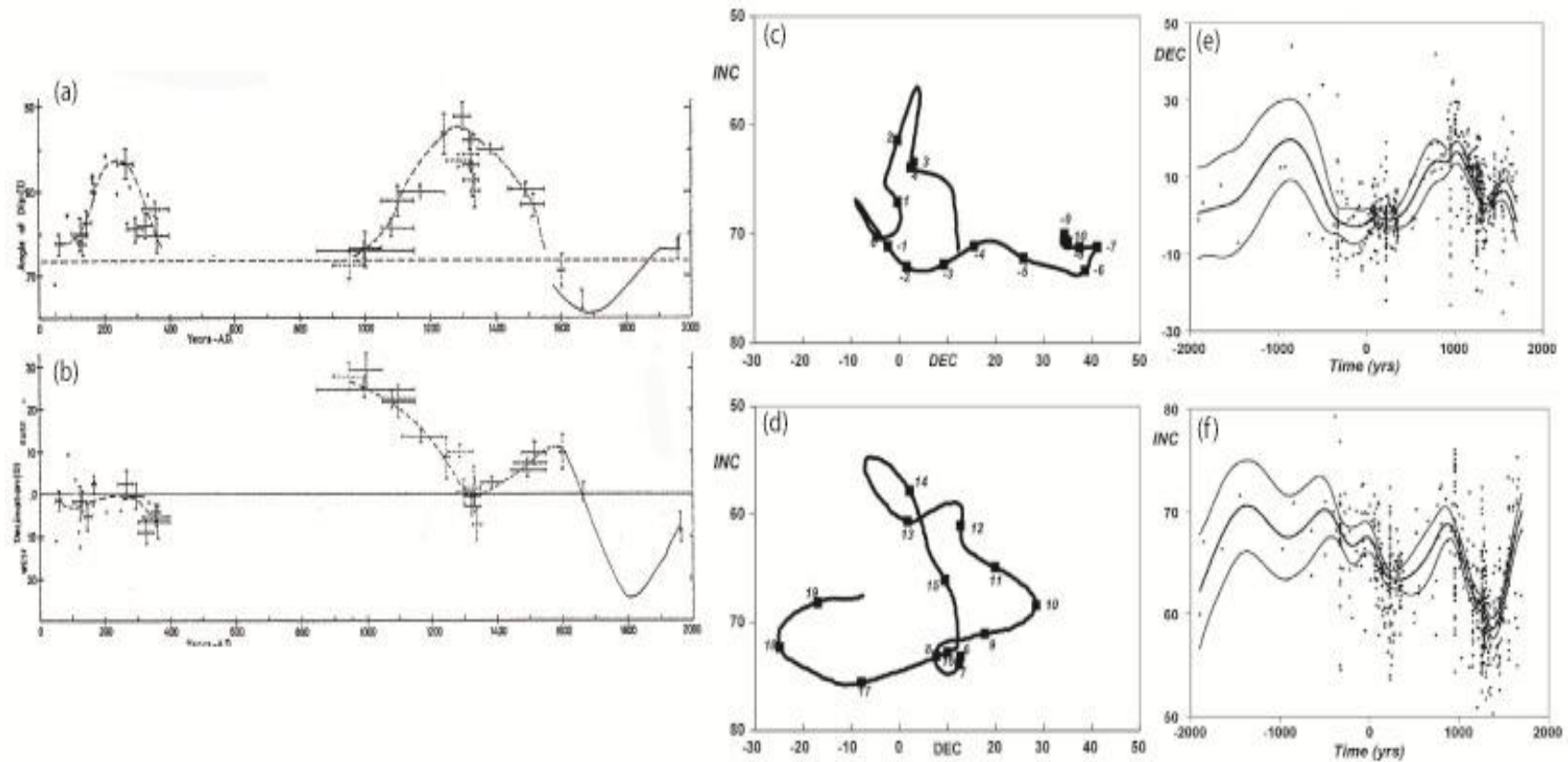


Figure 2.2: A composite image to illustrate the history and development of the British archaeomagnetic secular variation curve (SVC). On the left hand side is the first British archaeomagnetic SVC presented by Aitken et al (1963) shown as (a) inclination versus time and (b) declination versus time, for the past 2000 years. In the middle is the curve proposed by Clark et al (1988) shown on a Bauer plot as inclination versus declination. Time is shown along the curve and is in 100 years interval as BC (-) and AD. These data have been reduced to Meriden for the time span (c) 1000BC to AD600 and (d) AD600-1975. On the right hand side is the curve presented by Zanani et al (2007) shown as (e) declination versus time and (f) inclination versus time, for the past 4000 years; data have been reduced to Meriden and the calibration curve (thick line) surrounded by the  $2\sigma$  errors envelop (thin lines) as obtained by Bayesian modelling. © Wiley-Blackwell, Elsevier and John Wiley & Sons, reproduced with permission.

This curve is referred to as a secular variation curve, or SVC, and its genesis benefited from the coalescence of several factors in the preceding years: Mercanton's proposal that magnetic studies of geological material could be used to test theories on continental drift (1932), the establishment of the physical basis of the acquisition of thermal remanence (Néel 1952; 1955), Thellier's work on archaeological material (1938) and finally the publication of Fisher's statistical model (1953), which enabled these data to be averaged in a meaningful way. The concept that vector end points should be treated as if they were on the surface of a sphere (Fisher 1953) has become central to palaeomagnetic and archaeomagnetic studies.

Cook and Belshé, working at Cambridge University, were the first to publish an archaeomagnetic reference curve (SVC) for Britain. In an optimistic paper they predicted the wide appeal of this technique and calculated that this method could provide dates for fired features with associated errors of  $\pm 25$  years (Cook & Belsché 1958). At this point the curve ranged from AD 1950 to 1540 and was based on observatory measurements from London since 1578, extended back to 1540 by some extrapolated data from Rome. A selection of vector directions from Roman and later medieval sites were plotted onto the curve, but no attempt was made to order these archaeologically-derived data chronologically. This work was followed by Aitken and co-workers at the Research Laboratory for Archaeology and the History of Art in Oxford, who presented the first SVC that extended back into prehistory, covering the last two millennia (Aitken & Weaver 1962). These earliest studies were perhaps encouraged by the implicit assumption that the secular variation in the geomagnetic field occurred in a predictable pattern, but this assumption would also encumber them. A decade long program of intensive work by the Oxford team (Aitken 1970) on archaeomagnetic directional studies, resulted in the production of a SVC that tentatively covered the period from 0AD to the present day, with a significant gap during the 'Dark Ages', i.e. AD350-1000.



Despite the sanguinity about this new dating technique, these early papers often appeared to disregard what are now realised to be the limitations of archaeomagnetic dating. At one point it is referred to as being “similar to stylistic dating except that the characteristic attribute – the magnetic direction – is firstly invisible and secondly external to man” (Aitken 1960: 41), which is actually a major issue with regards to the application of this dating method. Regardless, the preliminary work carried out by the Oxford team provides perhaps the most comprehensive assessment of the three components required to create a SVC: declination, inclination and time, for around 100 sites. They made a serious attempt to incorporate the archaeological details, understanding that some archaeological dates are more reliable than others and that this aspect is challenging to quantify. Towards the end of the decade it was becoming clear that some periods appeared to provide more material to sample than others and, to some concern, results were being obtained with increasing frequency that were falling far from the expected curve (Hurst 1966). Here the reluctance to acknowledge that the SVC may not follow a logical or predictable pattern hindered advancement along this line of enquiry.

### **2.5.2 The period of establishment of British archaeomagnetic studies**

Ever since the establishment of the basic principles behind archaeomagnetic dating, it was realised that constructing past movements of the Earth’s magnetic field (EMF) could only be done empirically. Improvements in the spinner magnetometers employed to detect the magnetisation of materials allowed the intensity and direction of remanence in more weakly magnetised rocks to be measured with greater precision (Tarling 1975). The construction of magnetometers designed specifically for archaeomagnetic purposes (Molyneux 1971) encouraged further study in this area but, with ten years of work unable to create a continuous record of secular variation in the geomagnetic field, it appeared to be necessary to examine the potential of other approaches. Perhaps the most promising was to be found in palaeolimnology, as it had been demonstrated that freshwater lacustrine

sediments could provide a record of past secular variation in the geomagnetic field (Creer *et al.* 1972).

Magnetic studies were initially employed to interpret the lacustrine successions, where variations in declination with depth were used to provide stratigraphic information, and intensity and susceptibility were found to be useful for correlating records between cores from the same lake (Thompson 1973). The first attempt to apply magnetic studies of lake sediments specifically to reconstruct a palaeomagnetic record was on sediment cores retrieved from Loch Lomond, Scotland (Turner & Thompson 1979), which was able to produce a continuous record of secular variation extending back 7000 years. This study potentially offered a high-fidelity record of magnetic direction and appeared to confirm some of the features that were becoming apparent from the archaeological data. Less success was achieved with magnetic studies of British speleothems (Latham *et al.* 1979) or cave deposits (Noel 1986), as most stalagmite deposits in the UK do not carry sufficient remanence carrying materials and the rate of growth was too slow to provide the fine detail necessary to construct a SVC applicable to archaeological timescales. Furthermore, cave deposits are vulnerable to post-depositional chemical alteration and flooding events, which can distort the magnetic record.

Studies from other British lakes showed remarkable consistency in the recorded magnetic signatures for the post-glacial period (Turner & Thompson 1981; Thompson & Edwards 1982), but were limited by issues over chronological control. The independent dating of the cores from the British mainland relied heavily on the radiocarbon dating of organic materials within the sediments, leaving the possibility for the presence of old carbon through hill-wash or human activity around the lake. Although a total of 29 radiocarbon samples were collected from the British lakes sampled, 10 dates were rejected as unreliable, leaving 7 from Loch Lomond, 9 from Llyn Geirionydd and 3 from Windermere. This data rejection has resulted in the dated horizons for each lake not being evenly spaced down the sequence. It was

therefore necessary to assume that the rate of deposition was constant throughout the cores. A further assumption was that the “inclination error” remained constant, both between the cores from each lake (so that they could be combined) and over time, down the sequence. This error could mean that the inclination recorded by the sediment was up to 20° too shallow (Johnson *et al.* 1948) and experiments have suggested that the “inclination error” can vary between deposition events (Griffiths *et al.* 1957) and it has been noted that inclinations of vectors from lake cores are consistently low (Creer *et al.* 1972). Furthermore, it has been argued that it is ambiguous whether the magnetic signal relates to the deposition or consolidation of the sediment (Verosub 1977). Leading to the suggestion that a lag may exist between the time of deposition and the capture of the remanent magnetisation.

Nonetheless, it appeared that lake sediments did indeed record secular variation of the geomagnetic field and studies from other areas of the globe have noted the same phenomenon (for example Hirooka 1971; Stober & Thompson 1977; Creer & Tucholka 1982). As 80% of the geomagnetic field can be described by a dipole field, a simple dipole tilt model should enable the major features of secular variation to be elucidated on a global scale (Valet *et al.* 2008); therefore, lacustrine records should enable the main features of the palaeomagnetic record to be reconstructed for the Holocene (Nilsson *et al.* 2010). Unfortunately, the palaeomagnetic signature recorded by the British lakes did not agree with the magnetic signatures retrieved from other lake sequences worldwide (Turner & Thompson 1981). Suggesting two possible implications: the lacustrine sediments are not providing a true representation of secular variation in the geomagnetic field, or that secular variation was more complex than originally speculated and that non-dipole components have a greater impact on this type of recording mechanism. It is likely that both factors play a part but, regardless of the debate over the reliability or applicability of these data, these early studies on lacustrine records demonstrated that secular variation is not periodic in nature. Whilst this introduced many problems for workers hoping to reconstruct secular variation in the

palaeogeomagnetic field, it did reinvigorate a return to studying archaeomagnetic records.

### 2.5.3 Further developments

In Britain this return was led by Clark and co-workers (1988). Their seminal paper standardised the methods of collection and measurement of archaeomagnetic samples and extended the range of datable materials. Since its publication all practitioners in the UK, with limited exceptions, follow the methods as described by Clark *et al.* This paper also produced an updated SVC, displayed as two Bauer plots that covered the period from 1000BC to AD1975 and included 92 new magnetic directions. With the understanding that the geomagnetic field changes spatially, as well as temporally, came the need to produce regional records of secular change. It had now been demonstrated that data from an area of 500km radius can be used in the same SVC without introducing significant errors (Shuey *et al.* 1970; Noel & Batt 1990), with others suggesting that the area covered by individual SVCs should be ellipsoid, rather than circular (Suttie 2006). However, the method currently employed is to relocate all observations of the geomagnetic field that fall within a 500km radius to a central location, which in Britain is Meriden (52.43N; 1.62W), although recent developments may see a shift to relocating the curve to each site to be calibrated (Pavón-Carrasco *et al.* 2011).

Controversially, Clark and co-workers (1988) decided to also incorporate lake sediment data, although they did caution that it was to provide a broad confirmation of the changes as the SVC was built up. Others believed that this apparently continuous sequence of magnetic directions was misleading (given the paucity of understanding relating to the signal that lacustrine sediments were recording) and should not be included (Batt 1997). More recent work has suggested that there are difficulties comparing magnetic directions obtained from fired materials to those from sedimentary sequences (Gallet *et al.* 2002). Also, the decision taken by Clark *et al.* (1988) to systematically add 2.4° to the inclinations of

floor surfaces in order to correct for possible distortion of the magnetising field perhaps requires review. The most comprehensive and insightful analysis of the SVC provided by Clark *et al.* (1988) identified several problems with the methodology of its construction (Batt 1997). These include: the subjective interpolation between individual data points by freehand drawing; the lack of representation of individual data points; the lack of error assessment associated with the SVC; the extensive interpolation required in certain periods, due to the paucity of data points, and that the production of calibrated dates was by visual comparison with no measure of associated probability.

Despite subsequent efforts to raise awareness of the problems with the presentation and retrieval of information from the SVC and the need for an objective method to assess the data (Tarling & Dobson 1995; Batt 1998) the “Clark curve” became the accepted SVC to be used for calibrating archaeomagnetic directions for all British data. Although two calibration curves were published after it (Tarling & Dobson 1995, Batt 1997), they also presented the curves graphically, so in terms of the calibration process and production of calendar dates did not represent any significant progress from the “Clark curve”. Other laboratories, dissatisfied with these three different versions of the British SVC, chose to construct their own version (for example, Linford & Welch 2004) using the most up-to-date dataset. Although, this SVC included more data it was still based on the same mathematical procedures utilised by Batt (1997; section 7.3). Linford and co-workers (2004) were the first to recognise the potential of applying Bayesian modelling, as developed by Lanos (2004), to British data. The approach dealt with all the limitations highlighted by Batt (1997) and has provided a more reliable SVC for Britain (Zananiri *et al.* 2007), the first SVC with an associated estimate of error. This approach has been quickly established across Europe as the standard method of SVC construction (Pavón-Carrasco *et al.* 2011).

Other workers have attempted to broaden the application of the archaeomagnetic signal, with varying success, through exploring the potential of other aspects of the thermal remanent signal (Borradaile & Brann 1997; Maher *et al.* 2000) or widening the range of sources for the magnetic signal (Linford *et al.* 2005), including magnetic bacteria (Maher & Hounslow 1999). Work led by Borradaile and Brann (1997) attempted to take advantage of the observation that magnetic minerals lose their remanent magnetisation over time, as they tend to be affected by the contemporary field. This overprinting of geological magnetisations, relating to the genesis of the rock, has led to the development of viscous remanent magnetisation (VRM) dating. The theory was that if a block of rock was quarried and used in buildings it would acquire a VRM signal, and the intensity of that signal would be proportional to the length of time that the block had been in this new position as part of a building. This VRM would be identified as a higher temperature would be required to remove it. It is unclear how relocating a block of material would instigate the acquisition of a VRM signal. If the mineralogy was suspect to overprinting, surely this process would have commenced after formation. Furthermore, the studies conducted showed no clear relationship between the elapsed time and the temperature required to eliminate the VRM signal. It proved necessary to utilise another source, in this case documentary evidence to quantify the rate of change of the acquisition of VRM. At best this approach provided a relative method of intra-building comparison and only worked if all samples originated from the same quarry, thus avoiding issues regarding differences in mineralogy or grain size that would be expected if different sources or types of rocks were used.

Investigations into the presence of magnetotactic bacteria in sediments held the most potential for archaeological studies. These organisms form chains of ferrimagnetic mineral crystals within their cell envelope; therefore, any ambient magnetic field is effectively “sensed” by the entire bacterial cell. These bacteria live in wet, anoxic conditions and a variety of species exist, each with their own ecological niche, from soils and brackish waters to deep-sea sediments (Hesse &

Stolz 1999; Maher & Hounslow 1999). The presence of fossil bacterial ferrimagnets within sediments has prompted their use as a proxy for climatic changes and to provide a date for these changes (Linford *et al.* 2005). Whilst the presence of biogenic magnetite may be associated with increasingly wet conditions and the magnetic signal recovered appears to be a reliable record of the past magnetic field, there are difficulties in conclusively attributing changes in climatic conditions as identified through proxies to human agencies. Ultimately, this method has useful implications for Quaternary studies but the application of biogenic magnetic minerals to archaeological questions is probably limited to specific cases, such as the silting up of man-made wells or related features (Ellis & Brown 1998).

The widespread availability of increasingly powerful computers has enabled large datasets to be subjected to complex series of analyses and the results presented pictorially. A major landmark was the development of a three-dimensional simulation that demonstrates how the geomagnetic field has been sustained for billions of years (Glatzmaier & Roberts 1995). From the insights into the structure and dynamics of the geomagnetic field, provided by this simulation, there has been a shift of focus in palaeomagnetic studies towards developing global models of secular change using spherical harmonics (Korte & Constable 2003; 2005). This technique is influencing archaeomagnetic studies towards creating a single reference for the EMF (Lodge & Holme 2009, Pavón-Carrasco *et al.* 2008, 2009), but due to the influence of non-dipole components these do not provide the resolution necessary to date archaeological structures (Zananiri *et al.* 2007). This limitation is mostly due to the distribution and quality of the available data, which means that only large scale features in secular variation can reliably be resolved and that, due to accumulating uncertainties in the data processing, the temporal resolution is restricted (Korte & Constable 2008). Despite the limitations imposed by the modelling methodology, perhaps the most important point to remember is that any model can only be as reliable as the data used to create it. This is where this research project fits, as it is postulated that it should be possible to improve the

quality of the British archaeomagnetic dataset, enabling more representative models, whether regional or global, to be constructed.

#### **2.5.4 The future**

The past five decades have seen many developments in the practice of archaeomagnetism in Britain, including improvements in the theory, methodology and standardisation of archaeological practice (Linford 2006). For the most part archaeomagnetic dating in Britain has been dominated by studies of artificially heated materials. Therefore the technique has become a useful tool for archaeological chronology, enabling a particular suite of archaeological features from the last three millennia to be dated. As a dating method it remains under-exploited and there is still work to be done refining the SVC. This research is timely because producing a reliable description of the secular variation experienced by the geomagnetic field has several other potential applications (Sternberg & Damon 1983; Korte & Constable 2003; Le Mouél *et al.* 2005; Bakhmutov 2006), but the most pertinent for archaeological studies is the precision of the dates that can be obtained, as these vary for different archaeological periods. This research project will attempt to address this issue, by examining in detail the chronological assignment of the 100 or so magnetic directions that comprise the current SVC during the first millennium BC (chapter 4).

#### **2.6 Summary**

This chapter aimed to present the current situation through a historical narrative of the development of both Iron Age and archaeomagnetic studies in Britain. Both these areas of research will be applied extensively to the problem of improving the geomagnetic SVC for Britain. It was hoped that by understanding the developmental history behind these subjects it would be possible to make the most of the information they contain. Chronological frameworks are an integral part of any archaeological interpretation, but they are often restricted by the lack of precision in the dates available to the archaeologist. This issue is a particular



problem in the Iron Age, due to the perceived limitations of radiocarbon dating for this period (Haselgrove *et al.* 2001), specifically the period between 700-400BC where the radiocarbon calibration curve provides low resolution, (figure 2.1). Traditionally, assemblages of material culture have been used as chronological indicators, but it can be difficult to identify contemporaneous cultures when the wider landscape is considered. Whilst the stylistic and technological features of artefacts do change over time, that change is driven by social and economic forces acting within a society; attempting to reconstruct both aspects from artefacts is challenging and the results tend to be unsatisfactory. It has been argued elsewhere (Clelland 2006) that whilst chronologies developed from typological sequences represent the relative sequence of developments, they cannot date the absolute rate of changes observed in the archaeological record. The rate of change is important to understanding both the nature and causes of social development, which in turn affects archaeological interpretations of the social development in any individual society. A problem that becomes even more challenging, when Britain as an entity is considered, due to the degree of regionality that can be identified within the archaeological record for this period (e.g. Hill 1995a; Harding 2004: 3-5).

Archaeomagnetic studies offer a currently underexploited opportunity to provide dates for the Iron Age through the study of the Earth's past geomagnetic field, as recorded by archaeological materials. Chapter 3 will describe the physics underlying the application of archaeomagnetism to archaeological materials, before the associated age estimates are reviewed in chapter 4. If this study could also be extended to include analysis of the sedimentary record, this could provide a completely independent record of secular change in the geomagnetic field and this potential will be explored in chapter 6.

### **3. Current understanding of the fundamental aspects of archaeomagnetism.**

“Magnetism, as you recall from physics class, is a powerful force that causes certain items to be attracted to refrigerators.”

Dave Berry (1947- )

#### **3.1 Introduction**

The Earth is surrounded by a magnetic field, the geomagnetic field, so everything is penetrated by magnetic lines of force that humans do not experience in a direct way. Comparison with other planets in the solar system suggests that without the geomagnetic field the Earth's atmosphere would have been stripped away by the solar wind (Dunlop 2007). The most convincing display of the geomagnetic field, as a protective shield, is the occurrence of natural colour light displays observed in the night sky around the polar zones (Chapman 1936: 112). These are called auroras after Aurora, the Roman goddess of dawn; in northern latitudes they are known as *aurora borealis* and their southern counterparts as *aurora australis* and it is now understood that they are produced by the interaction of the solar wind with the geomagnetic field. This chapter will describe the phenomenon of the geomagnetic field, how its secular variation in the past can be recorded and will describe the specific events that can cause the contemporary geomagnetic field to be captured by archaeological materials and sediments. The main tenet of this thesis revolves around recognising the relationship between the physical event capturing the geomagnetic field and the event of archaeological interest, making understanding these aspects fundamental to this study. Together they can augment the central aspect of archaeomagnetic dating, the calibration or secular variation curve (SVC).

#### **3.2 Developments in understanding of the geomagnetic field**

The field of study originated with observations made at the Earth's surface from which Mercator postulated in 1546 that the point of a compass needle seeks

out a point on the Earth's surface and not in the heavens. Then, in 1600, William Gilbert, in his seminal work *De Magnete*, proposed that magnetism was a property of the body of the Earth as a whole (Wilson 2000), meaning that the Earth produces a field which has the same spatial pattern of lines of force as a bar magnet, i.e. it is dipolar. Later, Gauss (1839) demonstrated through the application of Laplace's equation that the magnetic field could be represented as a series of spherical harmonics. Thus was able to prove mathematically Gilbert's conjecture that the magnetic field was of internal origin and that it was dipolar. It was in the seventeenth century that observations confirmed that the geomagnetic field displayed secular variation (Gellibrand 1634). This led to the development of the dynamo theory of the geomagnetic field in the 20<sup>th</sup> century, which suggested that currents generated in the fluid outer core were sufficient to maintain the geomagnetic field (Bullard 1949). The dynamo is formed by a homogeneous, highly conducting and rapidly rotating fluid within the Earth. Usually a magnetic field generated by an electric current will fade away as the current decays but palaeomagnetic studies have demonstrated that the Earth has maintained a geomagnetic field for billions of years (Dunlop & Özdemir 1997: 3). This conundrum remained until the publication of a numerical solution to the magneto-hydrodynamic equations (Glatzmaier & Roberts 1995), which provided some validation for this theory. These equations describe the myriad factors that would interact in a rapidly rotating spherical fluid shell with a solid conducting inner core and successfully reproduced some key features of the geomagnetic field over 40 000 years of simulated time, including secular variation and magnetic reversals. They have been used to create a three-dimensional model of the spatial pattern of lines of force of the geomagnetic field (which can be viewed at <http://antwarp.gsfc.nasa.gov/apod/ap021125.html>).

It is generally accepted that the source of the geomagnetic field is located both within and external to the Earth's outer core (Langel & Hinze 1998: 18). The main internal source is generated within the Earth's outer core, whilst a minor component, magnetic anomalies, originates in the crust and upper mantle. Without

any external fields the geomagnetic field would extend indefinitely into space, but a stream of plasma from the Sun, called the solar wind, confines it to an envelope, referred to as the magnetosphere, (figure 3.1). The magnetopause and ionosphere are the outer and inner boundary, respectively, of the magnetosphere. Except during magnetic storms, around 98% of the magnetic field experienced on the Earth's surface is produced by a self-sustaining dynamo processes in the Earth's liquid outer core. The liquid outer core is conducting and carries electric currents which are the main source of the geomagnetic field. Other factors that contribute to the remaining 2% of the main field are the remanent and induced magnetisation in the lithosphere and the tidal currents in the solar wind.

It is generally believed that secular variation observed over periods of tens of years is of internal origin, whereas periods of less than a year are of external origin (Merrill *et al.* 1998: 47). The simplest model of this is an axial geocentric dipolar model, with small-scale flow patterns giving rise to the higher harmonics that form the non-dipole field (Bloxham & Gubbins 1985). Using classical electrodynamics and spherical harmonics this model can be expressed mathematically but the model is not perfect (Korte & Constable 2005; Korte *et al.* 2009). Previous studies suggest that the archaeomagnetic observations collected to date show a general, but not complete, agreement with the axial geocentric dipole model (Hamm-Yassi 1983; Kovacheva 1992). However, the disparity is small (around 2-3°) compared with the amplitude of secular variation that is observed for the past 2000 years (around 20°). It has been found that an inclined geocentric dipole best describes the present geomagnetic field (Valet *et al.* 2008) and generally it is believed that this simple model provides an adequate approximation of the geomagnetic field (Butler 1992: 4; Nilsson *et al.* 2010). Yet, the validity of this model is fundamental to the central aspect of archaeomagnetic dating, the SVC, as its construction is based on the principle of uniformitarianism.

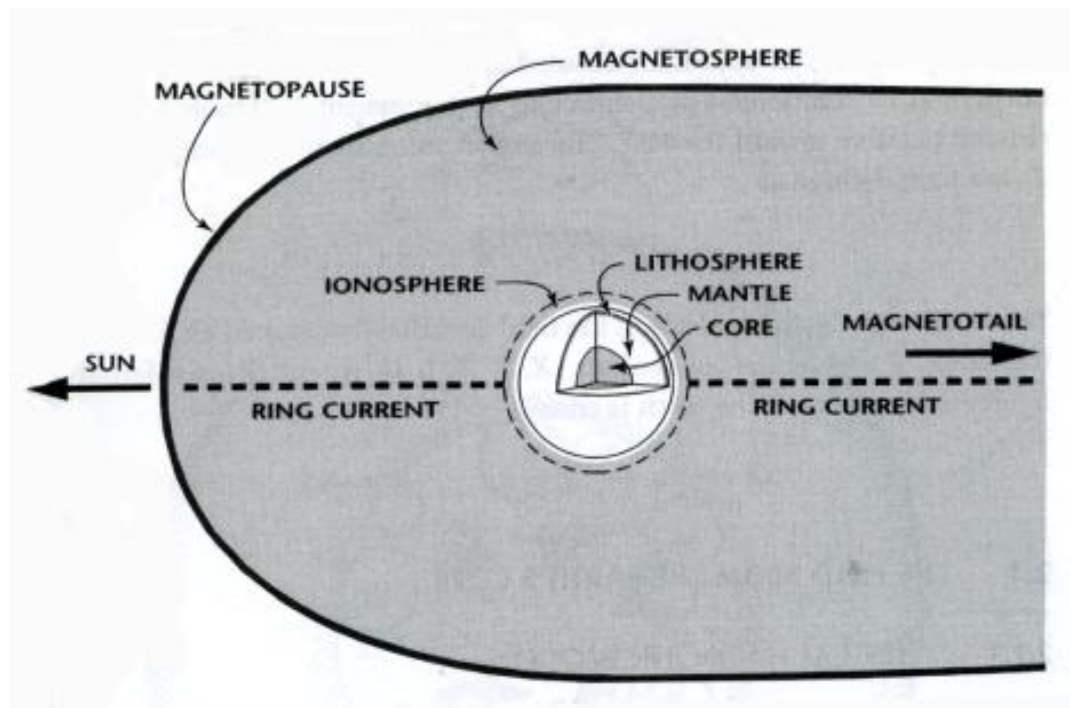


Figure 3.1: A schematic showing the source regions for the near-Earth geomagnetic field (Langel & Hinze 1998: 19 figure 2.1). © Cambridge University Press reproduced with permission.

### 3.3 The magnetic elements

It has been known in China since the 8<sup>th</sup> century AD, and rediscovered in Europe during the 14<sup>th</sup> century, that magnetic north and geographic north are not the same (Tarling 1983: 2). The angle between them is called the declination (or magnetic variation) and in geomagnetic studies is defined positive if it is east of geographic north and negative if it is to the west. The vertical plane through this direction is called the magnetic meridian and the angle of dip with respect to horizontal of a magnetisation from this plane is called the inclination (dip) and is defined positive downwards. Therefore, at present day in the northern hemisphere inclination is positive, whereas in the southern hemisphere it is negative. Historically, the study of the geomagnetic field has developed from studies carried out at the Earth's surface; therefore measurements have been made with a modified system of Cartesian co-ordinates (Langel & Hinze 1998: 19). The geomagnetic field has been resolved into horizontal (H) and vertical (Z) components, (figure 3.2). The horizontal component, H, is resolved into the

direction of the local meridian and X is considered positive towards north, Y is perpendicular to the meridian and considered positive towards the east. Finally Z, the vertical component is positive downwards.

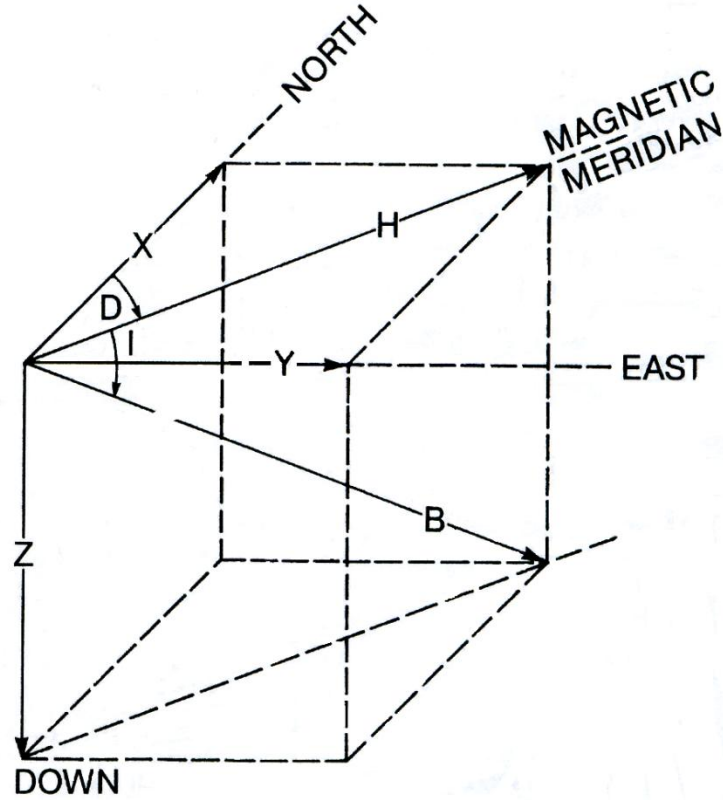


Figure 3.2: A schematic showing how the main elements of the geomagnetic field vector are resolved in Cartesian co-ordinates (Langel & Hinze 1998: 19 figure 2.2). The angles D and I are the declination and inclination, respectively. The vectors H and B are the horizontal magnetic field and the magnitude of the field respectively. © Cambridge University Press reproduced with permission.

From the Cartesian system presented in figure 3.2, the angles of inclination (I), and declination (D) can be defined as:

$$I = \arctan\left(\frac{Z}{H}\right)$$

Where  $-90 < I < 90$  and is measured positive down from the horizontal.

Equation 1

$$D = \arctan\left(\frac{Y}{X}\right)$$

Where  $0 < D < 360$  and is measured clockwise from North

Equation 2

However, magnetisation is a vector quantity such that it has strength, as well as direction, and the intensity (B) can be defined as:

$$B^2 = H^2 + Z^2 = X^2 + Y^2 + Z^2$$

Equation 3

Therefore, at any point on the Earth's surface the geomagnetic field can be completely defined by declination (D), inclination (I) and total intensity (B), which is referred to as full vector data. However, in this research only the direction component will be considered, as archaeomagnetic studies in Britain currently only extend to magnetic direction. There are historical reasons for this (section 2.5), but also it is more challenging to determine, and experimentally difficult to retrieve, information on magnetic intensity (Coe 1967; Kovacheva *et al.* 1998; Chauvin *et al.* 2000). However, it is hoped that in the future this will change (section 7.3.3).

Often it is necessary to convert magnetic directions between polar and Cartesian co-ordinates; by assuming the length of the vector to be 1 the method employed through this research is as follows:

$$x = \cos Dec. \cos Inc$$

Equation 4

$$y = \sin Dec. \cos Inc$$

Equation 5

$$z = \sin Inc$$

Equation 6

$$Dec = \tan^{-1} \frac{y}{x}$$

Equation 7

$$Inc = \sin^{-1} z$$

Equation 8

As each magnetic direction is a vector, in archaeomagnetic studies the direction is generally considered as polar co-ordinates. Therefore it is necessary to use a specific set of statistical procedures that considers vectors as points on a sphere. These statistical analyses are based on Fisher's (1953) work, as he derived a theoretical distribution, the Fisher distribution, which satisfies the requirements of archaeomagnetic studies. Although not originally derived for palaeomagnetic studies they do fulfil the three-dimensional statistical analysis requirement of palaeomagnetic studies. This section provides an outline of the mathematics that was applied to the fieldwork in chapter 5 and the data collated in chapter 6, the process being illustrated in figure 3.3. Given a sample of  $N$  observations drawn from a Fisher distribution,  $l_i$ ,  $m_i$  and  $n_i$  are the individual direction cosines for north, east and down directions, respectively, for each observation, where there are  $N$  observations. So the length of the overall direction is the sum of the individual unit vectors; this is the resultant vector  $R$  (figures 3.3 and 5.8), given by:

$$R^2 = \left( \sum_{i=1}^N l_i \right)^2 + \left( \sum_{i=1}^N m_i \right)^2 + \left( \sum_{i=1}^N n_i \right)^2$$

Equation 9

Using the mathematical relationships expressed in Equations 4 to 8 above and combining these with Equation 9, the declination of the mean direction ( $D_m$ ) can be given by:

$$\tan D_m = \frac{\sum m_i}{\sum l_i}$$

Equation 10



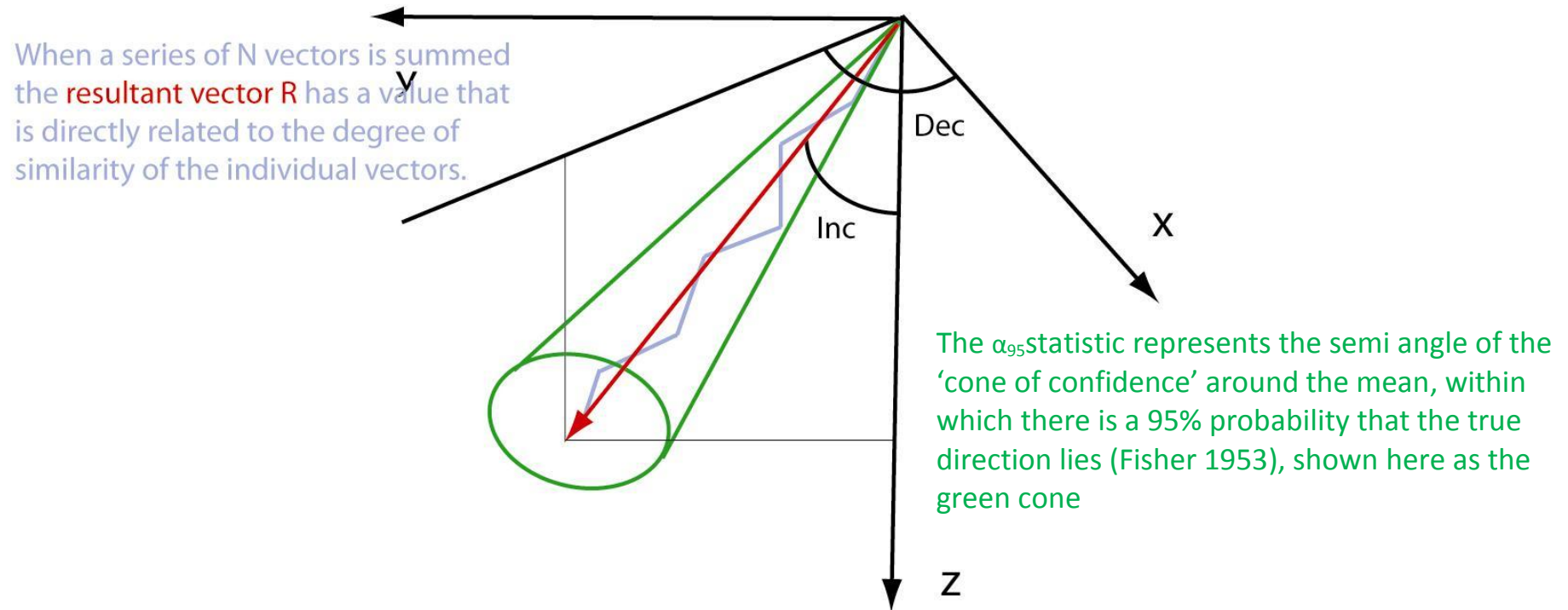


Figure 3.3: How the declination, inclination and  $\alpha_{95}$  values used in archaeomagnetism describe the mean direction relative to the magnetic vectors.

The inclination of the mean direction ( $I_m$ ) is given by:

$$\sin I_m = \frac{1}{R} \sum n_i$$

Equation 11

The best estimate of the precision ( $k$ ) for a mean direction (if  $k$  is  $>100$ ) is provided by:

$$k = \frac{N - 1}{N - R}$$

Equation 12

Hence, if  $N$  observations drawn from a Fishers distribution have a precision parameter  $k$  and the length of the resultant vector is  $R$ , then the observed mean direction will also be Fisher distributed about the true mean. Therefore, the true mean of a population will, with a probability  $(1-P)$ , fall within a circular cone of semi-angle  $\alpha_{(1-P)}$  about the resultant vector  $R$  and is given by:

$$\cos \alpha_{(1-P)} = 1 - \frac{N - R}{R} \left[ \left( \frac{1}{P} \right)^{\frac{1}{N-1}} - 1 \right]$$

where  $P$  is taken to be 0.05, to provide the 95% confidence interval.

Equation 13

### 3.4 Principles of rock magnetism for archaeomagnetic dating

With the establishment of the physical basis of magnetisation by Néel (1952; 1955), it was realised that at the atomic scale all materials can be regarded as magnetic, due to the motion of electrons both in orbit around the nucleus and electrons spinning around their own axes. When considering the atomic scale these magnetisations are a method of balancing the forces within atomic structures. The magnetic ordering provided by dia- or paramagnetism arises from electron orbital motions, so is in balance with the disordering effects of thermodynamic forces

within the atom. Therefore, the magnetic effects, although weak, because the dipole moments involved are small, can be broken down on heating. For each compound there is a specific temperature, the Néel temperature, at which the interatomic coupling breaks down and above this temperature all substances behave paramagnetically.

Materials that are commonly termed 'magnetic' are typically from the first transitional series, but particularly contain iron, cobalt and nickel. They exhibit strong magnetic effects resulting from a phenomenon known as ferromagnetism. In ferromagnetic minerals, to maintain balance in the electrostatic forces within the crystal structure magnetic exchange reactions occur, which cause the spins of the electrons to become aligned even in the absence of an applied magnetic field (figure 3.4). Ferromagnetic minerals remain magnetised in a particular direction, due to a balance in the competing energies that are present within the crystal structure between the ordering magnetic energies, which align the spins of neighbouring electrons and thermal energies generated by atomic vibrations, which add energy to the system and potentially randomise the structure (Tauxe 2002: 39). Within the crystal lattice atoms arrange themselves to minimise the competition between these magnetic ordering and thermal disordering energies. There are a number of different mechanisms by which remanence can be acquired and these are summarised in table 3.1. Understanding the mode of acquisition for a remanent magnetic signal is crucial as it can have a significant impact on the application of data, particularly with respect to the construction of a SVC.

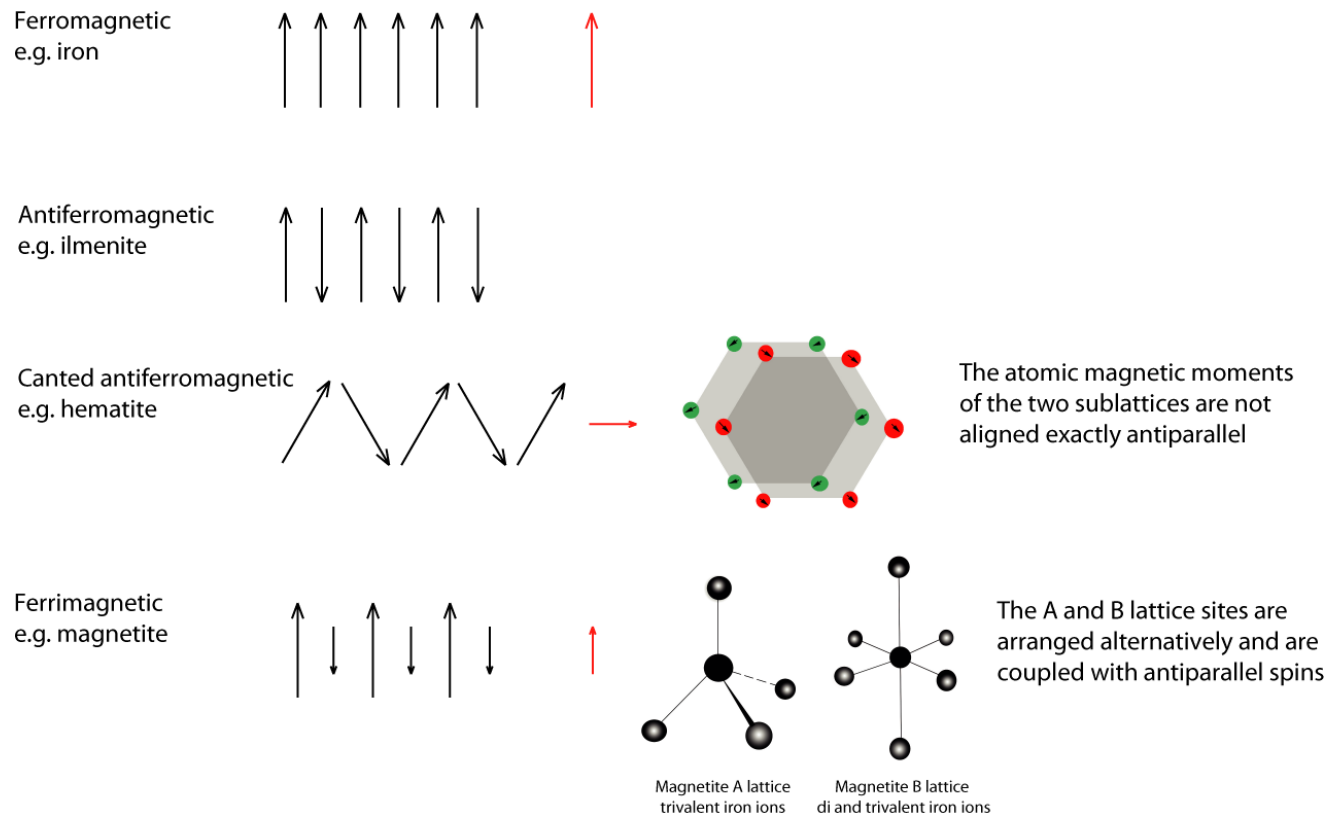


Figure 3.4: A series of images showing the different possible exchange spin structures that can occur within materials. The red arrow indicates the net spontaneous magnetisation that each will exhibit (Dunlop & Özdemir 1997: 25, from figure 2.3 with additions). The crystal structures of the two main magnetic minerals encountered in archaeomagnetism (magnetite and haematite) are also shown to illustrate how they lead to the observed magnetic properties.

Acronym	Term	Definition
NRM	Natural Remanent Magnetisation	A generic term given to the initial magnetisation of any sample before processing, to avoid any assumptions about the currently unknown origin of remanence, as the method by which magnetisation was obtained depends on the history of the sample.
TRM	Thermal Remanent Magnetisation	Remanence acquired by cooling from the Curie point (section 3.5.3 and 3.6) in the presence of an external magnetic field.
DRM	Detrital Remanent Magnetisation	Remanence acquired by sediments primarily deposited in water or air. This is a general term for the combination physical alignment processes represented by DDRM and PDRM
DDRM	Depositional Detrital Remanent Magnetisation	Remanence acquired as detrital magnetic particles become aligned with the Earth's magnetic field in the water column as they fall out of suspension.
PDRM	Post-depositional Detrital Remanent Magnetisation	Remanence acquired by the sediment as it consolidates after deposition.
CRM	Chemical Remanent Magnetisation	Remanence acquired by crystal growth within a magnetic field at a constant temperature.
PCRM	Post-depositional Chemical Remanent Magnetisation	Remanence acquired during the formation of a new magnetic material, e.g. the reduction of haematite to magnetite in organic rich deposits.
BRM	Bacterio Remanent Magnetisation	Remanence acquired due to the presence of bacterial magnetofossils within the sediment, associated with sediment deposition or chemical changes in the sedimentary environment.
VRM	Viscous Remanent Magnetisation	Remanence acquired by the presence of magnetic domains with low relaxation times within the mineral matrix.

*Table 3.1: Summary of mechanisms by which a remanent magnetisation signal may be acquired. The key point is that some of these reflect events of archaeological interest and others do not.*

Néel (1955) highlighted that the magnetic constituents in rocks and sediments are only a small proportion of the total material distributed within the non-magnetic bulk of the sediment and that these carriers are more or less pure oxides of iron which display ferrimagnetic or antiferromagnetic properties. These properties relate to the spin structures occurring within the crystal structure as part of the balancing forces within it. Any material that contains suitable oxides within its matrix is capable of retaining a magnetisation that could remain stable over geological time periods. This remanent magnetisation occurs within the crystal structure, in a region referred to as a magnetic domain. If a magnetic domain corresponds to a physical grain of the mineral crystal it is called a single domain magnetic material. If a single grain within the crystal structure is divided into many magnetic domains then it is referred to as a multidomain magnetic mineral. This latter case occurs in crystal structures with larger size ( $>0.5\ \mu\text{m}$ ) and reduces the overall energy of the system.

Within each domain the spontaneous magnetisation arising from the exchange reactions within the crystal structure is uniform, but the direction of this magnetisation varies from one domain to another. If the material is heated, thermal agitation of the crystal structure leads to a reduction of the spontaneous magnetisation, until at a critical temperature known as the blocking temperature, it disappears. The blocking temperature is dependent on the size and composition of the individual domain and, as most natural materials contain a range of grain sizes, they will also have a range of blocking temperatures (Tarling 1983: 25f). The relaxation time ( $\tau$ ) is dependent on temperature and the blocking temperature is where  $\tau$  is equal to about  $10^2$  to  $10^3$  seconds (Tauxe 2002: 57). There is a defined range of temperatures over which the relaxation time increases to geologically significant timescales, typically above  $200^\circ\text{C}$  and up to around  $500\text{--}700^\circ\text{C}$  dependent on the mineral composition (Néel 1955). Above the blocking temperature all the magnetic grains behave paramagnetically. This general theoretical model is based on observations of single domain magnetic minerals but it is assumed that the

balance between energies, applies equally to pseudo-single and multidomain magnetic minerals.

### **3.5 Application of rock magnetism to archaeomagnetism**

That some naturally occurring minerals are capable of retaining a magnetic signal is fundamental to the practice of archaeomagnetism (Linford 2006: 4). There are six naturally occurring iron compounds that exhibit ferrimagnetic and canted antiferromagnetic properties: magnetite, haematite, maghaemite, goethite, pyrrhotite and greigite. Of these the first three minerals (magnetite, haematite and maghaemite) tend to dominate discussions of magnetism in and on the Earth's crust (Evans & Heller 2003: 32). Magnetite is the most magnetic and the most ubiquitous magnetic mineral, occurring not only in igneous, sedimentary and metamorphic rocks but also in unconsolidated sediments, such as loess or lacustrine deposits, and it is manufactured by particular species of bacteria for navigational purposes (Maher & Hounslow 1999). The crystal structure of pure magnetite,  $\text{Fe}_3\text{O}_4$ , is cubic with a spinel structure, therefore the basic building block of the crystal lattice is a face-centred cubic framework (Battey & Pring 1997: 213). This structure contains two sub-lattices: A (tetrahedral) and B (octahedral) that are ferrimagnetically coupled (figure 3.4). Haematite,  $\alpha\text{Fe}_2\text{O}_3$ , is responsible for the red colouration in many sediments and its crystal structure is rhombohedral, so the basic building block is a hexagonal structure arranged in layers (Battey & Pring 1997: 211) that are ferromagnetically coupled within planes, but antiferromagnetically coupled between layers. However, the antiparallelism is not exact, giving rise to a spontaneous magnetisation (Tarling 1983: 40); this departure from antiparallelism is referred to as spin canting, so the magnetism displayed by haematite is called canted antiferromagnetism (Tauxe 2002: 43). Although, when compared to magnetite, haematite is only weakly magnetised and the rhombohedra structure makes haematite more thermally stable. Maghaemite is generally not considered when discussing fired sediments, as when heated to above  $350^\circ\text{C}$  it converts to haematite with a substantial decrease in spontaneous magnetisation (Tarling 1983: 39). However, it may make some contribution to the magnetic properties of other

deposits, for example aeolian or lacustrine. These iron oxides are also present in most geological materials suitable for archaeomagnetic analysis and display different magnetic properties, which can be related to differences in their crystal structure (figure 3.4). However, as they have little industrial application, their properties have received limited investigation outside palaeomagnetic studies (Tarling 1983: 42), but those qualities most commonly exploited in palaeomagnetism are presented in table 3.2.

### **3.5.1 Viscous remanent magnetisation**

The stability of a magnetic remanence is central to archaeomagnetic studies and this is related to the magnetic viscosity of a material, or the spontaneous change in magnetisation with time at a constant temperature. The theory originated from the seminal work by Néel (1955), where the model of the viscous effect in magnetism was introduced. The basic concept is that, even in the absence of an applied field, the magnetic moments of an assemblage of particles will tend to become randomly orientated over time, causing any initial magnetisation to decay. This effect is related to  $\tau$  (section 3.5) and the value of  $\tau$  is a measure of the probability that a grain will have sufficient thermal energy to overcome the anisotropy energy and switch its magnetic moment. In other words, grains with low  $\tau$  tend to track the change in the ambient geomagnetic field, because the grain has an unstable magnetic signal. Even in archaeomagnetic studies, which deal with a time frame in the order of  $10^3$  years, samples routinely undergo a process of magnetic cleaning in order to identify and remove any viscous remanent magnetisation (VRM).

### **3.5.2 Causes of secondary magnetisation**

Along with VRM there are other factors which may adversely affect the remanent magnetisation of archaeological significance. Of all the types of mechanisms by which sediments may capture a magnetic signal (table 3.1), one of



Name	Chemical formula	Magnetic behaviour	Coercivity, $H_c$ (mT)	Curie temperature, $T_c$ (°C)	Mass specific susceptibility, $\chi$ ( $10^{-6} \text{ m}^3 \text{ kg}^{-1}$ )	Occurrence
Magnetite	$\text{Fe}_3\text{O}_4$	Ferrimagnetic	10-40	580°C	400-1000	Soils, rocks and sediments
Haematite	$\alpha\text{Fe}_2\text{O}_3$	Canted antiferromagnetic	10 000's	675°C	0.3-2.0	Soils, rocks and sediments
Maghaemite	$\gamma\text{Fe}_2\text{O}_3$	Ferrimagnetic	10-40	590-675°C (Breaks down to $\alpha\text{Fe}_2\text{O}_3$ between 250-570°C)	250-450	Weathering product of magnetite in soils, rocks, sediments and dust. Presence indicates that the NRM is mainly CRM in origin
Goethite	$\alpha\text{FeOOH}$	Canted antiferromagnetic	Up to 10 000	70-125°C (Breaks down to $\alpha\text{Fe}_2\text{O}_3$ at 250-400°C)	0.3-1.3	Produced during weathering of soils, rocks, sediments
Pyrrhotite	$\text{Fe}_7\text{S}_8$ - $\text{Fe}_{11}\text{S}_{12}$	Ferrimagnetic	100	325°C (Breaks down to $\text{Fe}_3\text{O}_4$ at 500°C)	50	Some metamorphic and basic igneous rocks in reducing environments
Greigite	$\text{Fe}_3\text{S}_4$	Ferrimagnetic	60-100	330°C (Breaks down to $\text{Fe}_3\text{O}_4$ at 270-350°C)	169	Some sediments in reducing conditions, particularly anoxic sediments

*Table 3.2: The main magnetic properties of the six naturally occurring iron oxides relevant to archaeomagnetic dating. These data are indicative; actual values can show considerable variation and are strongly dependent on grain size and shape. Coercivity provides an indication of the strength of the internal magneto-crystalline forces acting within the magnetic grains. The Curie temperature represents the temperature at which the magnetic ordering within the crystal structure disappears. Mass specific susceptibility represents how easily the mineral can be influenced by an external magnetic field (Data from Dunlop & Özdemir 1997; Dearing 1999; Tauxe 2002).*

particular relevance to overprinting the magnetism in archaeological sediments is chemical remanent magnetisation (CRM). A CRM may be acquired due to the growth of new magnetic crystals, usually goethite, typically as a result of weathering. This process causes changes in the original remanent magnetisation recorded by archaeological sediments and can affect TRM or DRM signals. Depending on the extent of the weathering, it may be possible to compensate for any weathering affects and retrieve the original remanent signal, but generally it can only be identified as the cause for the loss of signal. This research encountered what is believed to be an example of chemical change due to weathering at the site of Tŷ Mawr, Anglesey (section 5.3.10). The hearths sampled had been left exposed for several months and had undergone a series of wet and dry cycles due to the heavy rains during the summer of 2007. Weathering can also have mechanical affects that can lead to a loss of signal, for example through exfoliation caused by frost action. This affect was observed at Market Deeping (section 5.3.5) where a feature first discovered in January 2010 remained exposed during a period of particularly cold and snowy weather before it was sampled in April 2010.

### **3.5.3 Precision and accuracy in archaeomagnetic directions**

The properties of naturally occurring magnetic minerals are affected by many inter-related factors, which are difficult to reproduce under laboratory conditions. Generally in archaeomagnetic studies heated materials are sampled, so the observed remanence was acquired during cooling of a thermoremanent magnetisation (TRM; section 3.6) and this is typically accompanied by a viscous component, i.e. viscous remanent magnetisation (VRM; section 3.5.1). The presence of VRM has implications for the laboratory processing of any archaeomagnetic material. The magnitude of the magnetic intensity depends on the magnetic mineral present, its composition, the rate of cooling and grain size (i.e. on the bulk susceptibility of the material). Therefore, it is important that as far as possible homogenous material is sampled. The precision with which the remanent directions of heated sediments have been determined is

represented by the  $k$  precision parameter (equation 12). Generally, in British archaeomagnetic studies, where several samples are collected from an individual feature, the  $\alpha_{95}$  statistic (equation 13) is quoted with the mean direction. This provides an estimate of the radius of the cone of 95% confidence about the mean (figure 3.3) and the smaller this angle, the less scatter is observed in the established field direction (section 5.2.5). There are several factors that can cause non-systematic directional deviations indicated by large  $\alpha_{95}$  values or low  $k$  values and generally it is not possible to identify a single factor as the predominant cause of dispersion (Weaver 1962; Gentles 1989: 276). The most commonly encountered factors are:

- Physical movement

One of the basic assumptions in archaeomagnetic directional determinations is that the material sampled has not moved since the last heating event. There are several processes that can cause archaeological material to move from its original position. Hearth materials can be compacted by superposition of a settlement or subsidence and can generate misleading results. Although these processes do not necessarily cause an increase in the  $\alpha_{95}$  statistic, generally any material that is not obviously still *in situ* is avoided. Evidence of these effects could be seen in a series of hearths observed in a section at High Pasture Cave, Western Isles (figure 3.5). Although excavations were taking place during this research, this site was not sampled for this reason. Evidence for physical movement was also observed at Street House, North Yorkshire (section 5.3.8) and Birnie, Morayshire (section 5.3.2). Weathering effects include chemical and physical changes through processes such as rehydration, frost shattering and shrinkage due to moisture loss and exfoliation effects (Tarling 1975). For example, the effect of rehydration and compaction may have affected the results from Tŷ Mawr, Anglesey (section 5.3.10) and frost action on those from Market Deeping (section 5.3.5).



*Figure 3.5: The north facing section of Trench 2 at High Pasture Cave from the north east. Eight hearth structures were identified in this section, but most appear to have experienced some slumping, particularly those to the left of the ranging rod, making them unsuitable for archaeomagnetic dating (Photograph © Steve Birch).*

- Insufficient heating

Another of the fundamental assumptions underlying archaeomagnetic directional determinations is that for heated sediments the Curie temperature for the particular mineral involved was reached (585°C for magnetite and 675°C for haematite) (Tauxe 2002: 57f). This is necessary for the magnetic domains to remagnetise in the direction of the easy axis of magnetisation that most closely parallels the ambient geomagnetic field and so acquire a TRM (section 3.6). Considerations of grain size, crystal structure and purity can reduce the blocking temperature, implying that outside laboratory conditions lower temperatures may cause the acquisition of TRM but these will still need to be in the region of 600°C. It is possible to reach these temperatures using open firings, as it is understood that ceramics production throughout British

prehistory were generally done in bonfires, which quickly reach temperatures in excess of 800°C (Gibson 2003), rather than in the domestic hearth as suggested by Hodges (1976). Indeed, bonfire firings have been demonstrated to reach these temperatures whatever the prevailing weather conditions by experimental archaeology (Woods 1989). A potential cause of the paucity of good magnetic data collected for the first millennium BC in the course of this research is insufficient heating, because it would have been unnecessary to always maintain a temperature in excess of 600°C in domestic hearths. Although the results from experimental archaeology (Gibson 2003) do suggest that these temperatures would have been reached briefly when the hearth was first lit.

- Inhomogeneity

Magnetic heterogeneity will occur in naturally occurring sediments from the microscopic level (with single and multi-domain magnetic minerals) up to gross magnetic differences in the choice of building materials. The remanence acquired differs depending on the types of magnetic minerals present and their grain sizes. Yet it has been suggested that an inhomogeneous distribution of magnetic grains, with different coercivities within a sample matrix, does not cause magnetic distortions leading to directional deviations (Tarling *et al.* 1986). Instead, it is larger scale inhomogeneities that are associated with the greatest scatter. Therefore the presence of foreign objects (e.g. stones, ceramics) will have the most significant impact on precision and accuracy of the recorded signal, particularly in sediments. Recent work suggests that the relative percentages of sand, clay and silt may impact on the precision of the archaeomagnetic direction and that the silt content may be an important consideration (Lengyel *et al.* 2011). When applied to the study of archaeomagnetism, there are two main mechanisms by which a remanent signal of archaeological interest is acquired these are: thermal remanent magnetisation (TRM), depositional detrital magnetisation (DRM) and chemical remanent magnetisation (CRM); TRM and DRM are encountered more often in archaeological excavations in Britain, so these will be discussed in detail in sections 3.6 and 3.7.

### **3.6 Thermoremanent mechanisms**

On cooling the magnetic domains remagnetise in the direction of the “easy” axis that is mostly parallel to any ambient magnetic field. Once the temperature has cooled below the blocking temperature for a particular domain the  $\tau$  is increased such that the magnetic direction within that grain is “blocked”, i.e. it can no longer alter (Tauxe 2002: 58). As long as the blocking temperature for any domain is above 200°C the magnetic direction acquired is stable over geological timescales. The overall TRM signal is understood to be a net effect of the reaction of all the magnetic domains present within the material to cooling from temperatures above their respective blocking temperature and this process is depicted in figure 3.6. Of course if the Curie temperature (section 3.5.3) was not reached then not all the domains present would have re-set their magnetic direction (Tarling 1983: 27). This theory applies equally to single, pseudo-single and multi-domain magnetic minerals, because domain walls can be blocked, depending on the strength of the energy barriers pinning down movement of the domain walls. Domains or domain walls with blocking temperatures below 200°C will be unable to retain a memory of the applied magnetic field, so will tend to change more rapidly and will track changes in the geomagnetic field generally without the need to be reheated (Tarling 1983: 28). This partial overprinting of the TRM is called viscous remanent magnetisation (VRM; section 3.5.1) and these effects must be identified and removed when dealing with TRM (section 5.2.4).

#### **3.6.1 Advantages and limitations of TRM**

One of the most important aspects of archaeomagnetic dating of fired features is that there is a direct relationship between the event being dated and an event of archaeological interest. This requirement was recognised very early on (Aitken 1960) and enables it to be easily incorporated into any archaeological narrative of a site. It also has had an impact beyond the confines of any single archaeological site; for

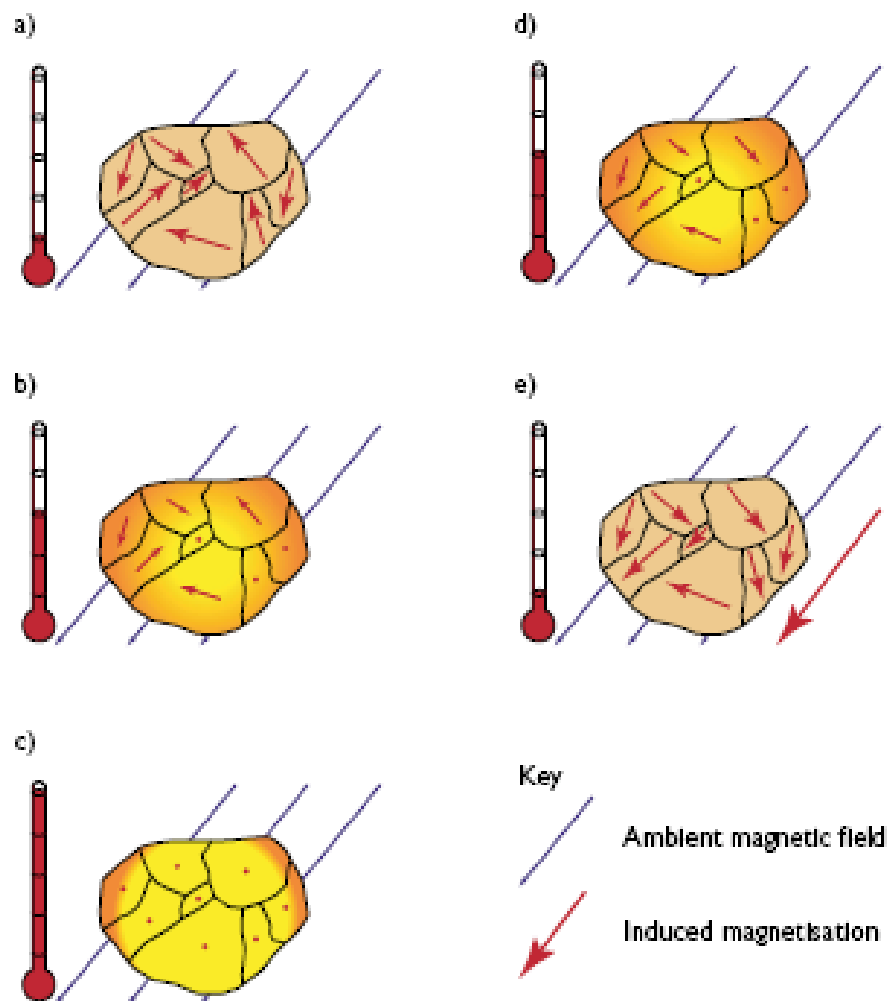


Figure 3.6: Series of images showing how TRM is acquired: a) initially magnetic domains within a grain of material are magnetised in random directions that cancel each other out; b) and c) as the sample is heated the domains demagnetise as the temperature exceeds their respective blocking temperatures; d) during cooling the domains remagnetise in a direction close to the prevailing ambient magnetic field; e) this results in a net magnetisation within the sample (Linford 2006: 4, figure 2) ©Paul Linford, English Heritage, reproduced with permission.

example, at Mine Howe on Orkney (full details in appendix 2). Archaeological evidence from the excavated structure identified as a workshop included clay moulds for “doorknob” spear butts, traditionally dated to 3<sup>rd</sup>-5<sup>th</sup> centuries AD (Card *et al.* 2005). Archaeomagnetic dates for a smithing hearth put the last use at 100BC to 100AD (Outram & Batt 2004), which effectively suggests that the spear butts were being

produced at least 200 years earlier than researchers had previously believed. Additionally, the magnetic signal recorded by TRM tends to be stable over archaeological timescales, although there is always the possibility of the presence of a viscous component. Due to the inhomogeneity of naturally occurring minerals, and the range of processes involved in the production of soils and sediments, there will always be some minerals present within the material that are magnetically less stable. However, these effects are usually not significant and are easily identified and removed during routine processing of archaeomagnetic samples.

An important problem with TRM is the potential effect due to the proximity of strongly magnetic features, or parts of the same feature (Lanos *et al.* 1999), which can cause several problems, potentially resulting in misleading results, including:

- The recording of a locally distorted field during the cooling event, rather than the actual geomagnetic field. A potential problem if the cause of the anomaly is contemporary with the fired feature; for example, a volcanic eruption (Rolph *et al.* 1987) or from the magnetisation of the feature itself (Harold 1960a; Márton 2003), by inducing an anomaly field. However, it is generally understood that this affect is unlikely (Bucur 1994), but by employing a systematic sampling strategy across the heat affected area it should be possible to identify and allow for any interference.
- The generation of a large secondary component, if a magnetic feature such as a railway line or power cable was later than the fired feature and their magnetisation was strong enough to influence the magnetism recorded by the fired feature. These may cause the overall magnetic signal to appear to have two apparently stable, but different, directions, which may be difficult to differentiate between (Lange & Murphy 1990). To date there have been few recorded incidents of this interference being the sole issue with a TRM signal; examples include suspected interference due to nearby railway lines at



Bernalda, Italy (Hoye 1982) or metallic fencing surrounding excavations at Regensburg, Germany (Schnepp & Lanos 2005), which does raise the question of identifying this phenomenon.

- Distortion of the ambient magnetic field during the collection of samples can also lead to the orientation of the individual specimens in the field being incorrect. The source of this distortion could be a modern feature, or it could be due to the magnetisation generated by the feature being sampled. This is only a problem with the use of magnetic compasses during sample collection; for example the effect of power cables was identified at Scot's Dyke, North Yorkshire (Karloukovski & Hounslow 2006), so this potential problem should be routinely checked during the field work and if necessary corrections applied.

### **3.7 Depositional remanence mechanisms**

Although both water-lain and airborne sediments can potentially record a DRM signal, in this research the focus will be on water-lain sediments, as this is the major mechanism by which DRM records of the geomagnetic field are produced during the first millennium BC in Europe. Lakes are inland bodies of water and are ecosystems, so biologically active; therefore, bioturbation of any accumulated sediment on the lake bed is likely. The lake bed is an accumulation of inorganic silts, which can record the geomagnetic field direction and can also contain organic material. Yet there are circumstances where the potential for bioturbation of the sediment accumulated at the bottom of lakes is reduced, i.e. meromictic lakes, with a flat and broad lake bottom where the deepest layers of water do not intermix. These circumstances provide low energy, anoxic environments, which produce sediment sequences suitable for studies of palaeosecular variation of the geomagnetic field (Zillén *et al.* 2003). Similar situations can be found on archaeological sites, for example at the bottom of well shafts or at the base of drainage ditches.

The acquisition of TRM is related to heating events which initiate changes in the spontaneous magnetisation of individual domains, whereas the acquisition of detrital remanent magnetisation (DRM) operates at the macroscale and includes the physical processes involved in the deposition of water-borne sediments, such as clays. Fine-grained clays tend to contain single domain magnetic minerals (typically magnetite) and the direction of the spontaneous magnetic moment within each domain is randomly orientated, because it was determined by the axes of the crystal structure. In the water column these grains tend to become aligned with the ambient magnetic field. As long as the water is relatively still, gravitational forces will tend to pull the particles to the bottom of the water column, where they will form a layer magnetised in the direction of the magnetic field (McNish & Johnson 1938), illustrated in figure 3.7.

Since this concept was first advanced a series of studies have been conducted to determine its feasibility (summarised in Verosub (1977) and Katari (2000)) and it was recognised that other forces intimately associated with the deposition process could also contribute to the direction of the remanent magnetisation. These included the shape of the particles, the effect of Brownian motion (Griffins 1957; Griffiths *et al.* 1957), slope of the bedding plane (King 1955), the presence of water currents (Rees 1961) and the limitations of laboratory techniques to recreate natural conditions (Hamilton 1967). However, research into aquatic chemistry has confirmed that fine grained sediments, with a particle size of around  $2\mu\text{m}$ , tend to flocculate and the magnetite grains become incorporated into larger flocs (O'Melia 1989; 1998).

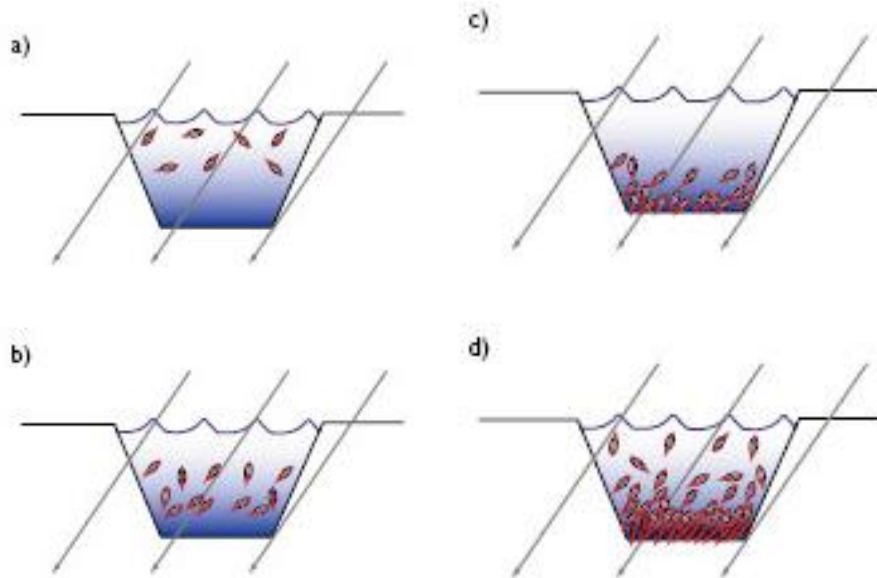


Figure 3.7: Series of images showing how DRM is acquired: a) sediment particles each with a weak magnetisation settle out of suspension in calm water; b) and c) as they fall through the water column they rotate to align their internal magnetic directions with the EMF; d) once settled at the surface/water interface the weight of sediment accumulating on top of the particles “locks” them in place leaving a layer magnetised in the direction of the Earth’s field (Linford 2006: 5 figure 3) ©Paul Linford, English Heritage, reproduced with permission.

The implication of this observation is that Van der Waals forces and viscous drag are also factors that can impact on the direction of the remanent magnetisation in water-lain sediments (Katari & Bloxham 2001). Furthermore, it is possible that a single floc may contain several magnetic grains, so the net direction of the remanent magnetisation may not be the sum of the magnetic particles within the floc because different orientations of the particles within the floc may result in a partial cancellation of individual magnetic directions (Tauxe *et al.* 2006). This is perhaps the best theoretical explanation put forward to explain why the magnetic intensity recorded by sediments was considerably lower than the strength of the applied field (Johnson *et al.* 1948).

One of the primary considerations in this research, when investigating the potential application of DRM, was the accuracy with which the sediment recorded the contemporary geomagnetic field. Unconsolidated sediments with a high rate of deposition, such as varved or lake sediments, are considered to potentially provide high temporal resolution records of remanent magnetisation (Roberts & Winklhofer 2004). Some early studies attempted to derive formulae to quantify and correct for the variety of inter-related factors that, in laboratory simulations, appeared to have straightforward and systematic effects (for example King 1955; Griffins 1957). However, subsequent studies suggested that DRM is a complex phenomenon, particularly when it was hypothesised by some workers that certain alignment processes can take place after deposition (Irving 1957). Therefore, it was deemed necessary to differentiate between depositional DRM (DDRM) and post-depositional DRM (PDRM). Some researchers have suggested that it is difficult to distinguish between these two mechanisms in natural sediments (Verosub 1977) and the laboratory experiments that appeared to support the PDRM method of acquisition have been criticised for not replicating natural conditions by using de-ionised water (Katari *et al.* 2000), although this has now been partially addressed (Carter-Stiglitz *et al.* 2006). This debate on which mechanism is actually responsible for producing the series of magnetic data observed in lake cores has been seen as limiting the capacity to determine the true nature of the secular variation of the geomagnetic field. This is a crucial point for the purposes of constructing a SVC, because if real the interval between these two events would have a significant impact on the accuracy of dates produced from a SVC that incorporated lake sediment data.

### **3.7.1 Differences between DDRM and PDRM**

In order to fully understand the challenges of deriving the secular variation of the geomagnetic field from water-lain sediment sequences, it is necessary to describe the perceived differences between the two recording mechanisms. For both

mechanisms the theoretical models emphasise the physical processes involved with deposition. DDRM focuses on interactions at the sediment/water interface; therefore, factors such as bottom currents, bedding-plane slope and fluid dynamics have to be balanced against gravity and the shape of the aggregated detrital material in suspension (Griffiths *et al.* 1957; Katari & Bloxham 2001). Three limitations were postulated with DDRM: the presence of an “inclination error”, which could mean that the inclination recorded by the sediment was up to 20° too shallow (Johnson *et al.* 1948); the effects of a “bedding error” (King 1955) and the impact of the “current rotation effect”, which can cause errors in both the declination and inclination recorded by the sediment (Rees 1961). Furthermore, in environments with slow deposition rates, this type of recording mechanism is particularly vulnerable to bioturbation (Verosub 1977). These have led most workers to believe that the magnetic signal recorded in sediments is acquired many tens of centimetres below the sediment/water interface via PDRM (for example, Carter-Stiglitz *et al.* 2006; Liu *et al.* 2008).

The currently accepted mechanism for the acquisition of PDRM is based on the rotation of magnetic particles within fluid-filled voids (Collinson 1965). This implies that when the water content drops below a critical value the magnetic particles can no longer rotate so the magnetisation becomes “locked”. It is likely that the critical water content will be characteristic of any given sediment and will be related to size, shape and mineralogy of both the magnetic minerals and the bulk sediment. The advantage of this mechanism is that it is not likely to incur any inclination error in the recorded magnetic direction. However, with respect to using these sediments as records of secular variation in the geomagnetic field, there is the important issue of when the magnetic direction becomes locked (Turner & Thompson 1981; Creer & Tucholka 1982; deMenocal *et al.* 1990; Stockhausen 1998; Ojala & Tiljander 2003; Roberts & Winklhofer 2004), which is believed to be related to a myriad of factors, the most important are considered to be sediment concentration and/or water content (Carter-

Stiglitz *et al.* 2006), meaning that it will be challenging to determine an age for the recorded direction and the temporal difference will alter between sediments for the same reasons as the critical water content. Furthermore, there is some evidence to suggest that the lag between the deposition event and the “lock-in” time is substantial (Løvlie 1974) and even in annually laminated sediments it can be around 100 years (Saarinen 1999), whereas in marine deposits estimates of “lock-in” time in the region of 300-3000 years have been given (Roberts & Winklhofer 2004).

### **3.7.2 Advantages and limitations of DRM**

It is apparent that British lake sequences appear to hold a stable remanent magnetisation (Creer *et al.* 1972) and evidence from modern analogues suggest that magnetisation in sediments is PDRM (Batt 1999). However, more recent research suggests that if the natural fabric of the sediment is preserved during sampling there is no evidence for PDRM (Katari *et al.* 2000) and no compelling support for a significant delay remanence acquisition through PDRM (Tauxe *et al.* 2006). This observation suggests that DRM is captured instantaneously and bioturbation only provides a cycle of re-suspension, and that this randomising affect only reduces the net magnetisation. Other experiments suggest that, even after settling, mechanically unstable grains within the sediment can still disorient due to Brownian motion, so demonstrating that PDRM has a crucial filtering affect (Carter-Stiglitz *et al.* 2006). It is suggested that the impact of mechanically unstable grains in an essentially mechanical recording process can be monitored and treated in the same manner as viscous remanent magnetisation (VRM; section 5.2.4) for processes taking place within the crystal structure of magnetic minerals. Furthermore, of all the processes that cause “inclination error” in palaeomagnetic studies generally, DRM is perhaps one of the least significant (Tauxe 2005). The laboratory simulations have only used specific materials, mostly deep sea sediment or varve material, both of which are very different to the lacustrine environment of British lakes. Therefore, it is not clear if the conclusions drawn from

laboratory simulations are actually applicable to other types of sediments, or if they are special cases restricted to those sediment types; particularly as particle shape and size, or floc size, are often quoted as being important factors. A different problem, that is perhaps more pertinent to British lakes, relates to deposition rate, because it is generally assumed that the deposition rate in the lakes sampled is fairly constant. A recent study in the English lake district has demonstrated that the rate of sediment flux has altered during the past 5500 years (Hatfield & Maher 2009), suggesting that assumptions regarding deposition rate may be a source of error in the British lake dataset.

The differences between how thermo and detrital remanence are recorded is fundamental and some believe that makes them difficult to compare objectively (Nourgaliev *et al.* 2005). However, if it is accepted that DRM is capable of instantaneously recording the ambient field as TRM does, then lake data present the same two issues encountered with archaeological material, i.e. sample collection and relating the available dating evidence to the event of interest. So, the view taken here is that many of the difficulties in previous data sets are more likely due to poor dating of the sediment cores, rather than the method of acquisition of remanence. The “time lags” are probably due to differences between the actual age of a magnetic signal and the age inferred from other dating evidence applied to the core, or result from undetected changes in the sediment flux rate (McMillan *et al.* 2002). Therefore, if these problems can be overcome it should be possible to combine TRM and DRM archives of palaeogeomagnetic secular variation (SV). The main advantage of incorporating SV recorded by DRM is that it provides a near continuous record of changes in the geomagnetic field, which depending on the sediment, is potentially a high resolution record. If attained this would enable trends in geomagnetic SV over a particular geographical region to be studied in detail which, has implications beyond the construction of SVCs, especially if the series of changes can be independently dated.

### 3.8 Summary

The Earth has a substantial magnetic field such that everything around us is penetrated by magnetic lines of force that we do not experience in a direct way. General understanding of the geomagnetic field states that it behaves like a bar magnet and possesses two poles, conventionally called north and south, but this is only an approximation of the observed geomagnetic field. Gauss and his contemporaries observed that the Earth's field is not static and current understanding of its behaviour over geologic timescales reveals that the position of the geomagnetic poles appears to precess around the geographic poles (McElhinny & McFadden 2000: 12). This gradual change in the geomagnetic field with time is called secular variation and is observed in all of the magnetic elements: declination, inclination and intensity. Superimposed over this movement of the dipole field are some other effects, believed to represent the combined effects of growth and drifting of the non-dipole components of the geomagnetic field. The long-term changes represented by secular variation are fundamental to the study of archaeomagnetism (Linford 2006: 3).

This research is concerned with improving the resolution of the first millennium BC section of the British archaeomagnetic secular variation curve. This work will be achieved by applying relative and absolute dating evidence derived from archaeological material. This chapter set out to introduce the planetary setting in which the various geomagnetic effects involved occur, in order to place this research in a proper framework. It has also provided the physical theory behind the most likely explanation of the phenomenon of the geomagnetic field and described the two most commonly encountered mechanisms by which the ambient geomagnetic field is captured by archaeological materials or Holocene sediments. It has also highlighted the fundamental differences between these two acquisition mechanisms, which has a significant impact on the potential for combining the different archives of magnetic data available for Britain during the first millennium BC. These differences will be



expanded on and the problems and potential methodologies for applying dating evidence to them will form the focus of chapters 4 and 6.

## **4. A procedure for identifying and evaluating the chronometric placement of magnetic data recovered from archaeological material**

“The last and perhaps most important source of directional scatter is the imprecision of the archaeological age estimates” (Márton 2003: 678)

“He learned by marvellous archaeological technique, the story of all earlier human peoples”  
Olaf Stapledon, “Last and First Men” 1930

### **4.1 Introduction**

Given that the primary aim of this research was to reconstruct past geomagnetic secular variation using studies of the geomagnetic field, as recorded by archaeological and geological materials, it was necessary to collate as much of the relevant data as possible. In order to identify and characterise short timescale changes in the Earth’s magnetic field (EMF), it was important to assess the quality of the data to ensure that all of the available data were fully exploited. A large part of this research involved data collection and meta-analysis of the assembled dataset, so four sources of data were examined:

1. The data in the current British secular variation curve (SVC) (Zananiri *et al.* 2007), which formed the starting point for this research;
2. Literature searches and communication with other archaeomagnetic laboratories to identify any new archaeomagnetic data and to collect together previously unpublished data, particularly laboratory reports;
3. A programme of sampling of fired material from on-going excavations at potential Iron Age sites (discussed further in chapter 5).
4. Collation of other palaeomagnetic data from geological material relevant to the first millennium BC, such as lake sediment records (discussed further in chapter 6);

This chapter will describe the first two levels of data collection and provide details on the sources of the data retrieved from archaeological sites that could be used to construct the new British SVC. It will then describe the methods used to assess the quality and reliability of each data point, followed by a general description of how the age assignment was determined for each of the archaeomagnetic directions. Full details on the actual method employed for each direction, on a site-by-site basis is presented region-by-region in appendix 2. Finally, in order to demonstrate the methodology devised to obtain an age assignment for each magnetic direction, a series of case studies will be presented. These were selected to not only highlight the success and flexibility of the method but also enable a discussion of its limitations.

## **4.2 Collating the data**

An initial survey of the most recent British dataset (Zananiri *et al.* 2007) revealed that there were 78 magnetic directions which had dates falling within the first millennium BC; this number was increased to 115 by including the first century AD. The decision was made to include the first century AD, because this small overlap would help in later stages when analysing the data (section 7.5) and would enable the inclusion of late Iron Age/early Roman transition sites. The directions currently in the British dataset that fit these criteria are from 59 different archaeological sites, that span the entire country, from the most southerly and westerly part of the UK, Scilly (50.00°, -6.30°), as far north as Shetland (59.88°, -1.30°) and east to Kent (51.30°, 1.40°). However, this spread is not evenly distributed across the country (figure 4.1) and makes it clear that much of the previous work has concentrated on southern areas and, particularly, England. This original distribution appears to reflect the location of most of the archaeomagnetic laboratories that have been able to routinely undertake directional studies: Oxford (the earliest work), London, Portsmouth and Bradford. The directional data for archaeological material in the current British reference curve are published (Clark *et al.* 1988; Tarling 1991; Zananiri *et al.* 2007) and along with

international data are readily available via the online databases archived and maintained by the National Geophysical Data Centre (NGDC [www.ngdc.noaa.gov/geomag/palaeo/shtml](http://www.ngdc.noaa.gov/geomag/palaeo/shtml)) or the Magnetism International Consortium (MagIC <http://earthref.org/MAGIC/>). Contact with other laboratories and literature searches have yielded many new directions previously not included in the database, in particular the inclusion of the considerable archives of archaeomagnetic work undertaken by GeoQuest Associates and work done at Lancaster University. These have enabled the total number of magnetic directions examined to reach 232 from 98 different archaeological sites (figure 4.1 and appendix 1). Therefore, it has been possible to double the dataset that relates to the first millennium BC, which has resulted in a more even distribution of sites across the British Isles, although there are still gaps.

### **4.3 Assessing the data**

As previous attempts to construct SVCs have highlighted (Sternberg & McGuire 1990b), it is important that any SVC reflects the true strengths and limitations of the archaeomagnetic method. In this way more confidence can be placed in the resulting pattern of geomagnetic variation. Although there is on-going research into defining and modelling the palaeogeomagnetic field (for example, Donadini *et al.* 2009; Lodge & Holme 2009), a unique aspect of this project is the reappraisal of the current archaeological dating assignments of the directional data within the British archaeomagnetic reference curve. It is argued that the reappraisal of the currently associated archaeological dating, of the directional data within the British archaeomagnetic reference curve, is an important aspect of any attempt to describe the palaeogeomagnetic field. When developing the dataset for a SVC there are primarily two main aspects to consider:

- the reliability of the magnetic data and

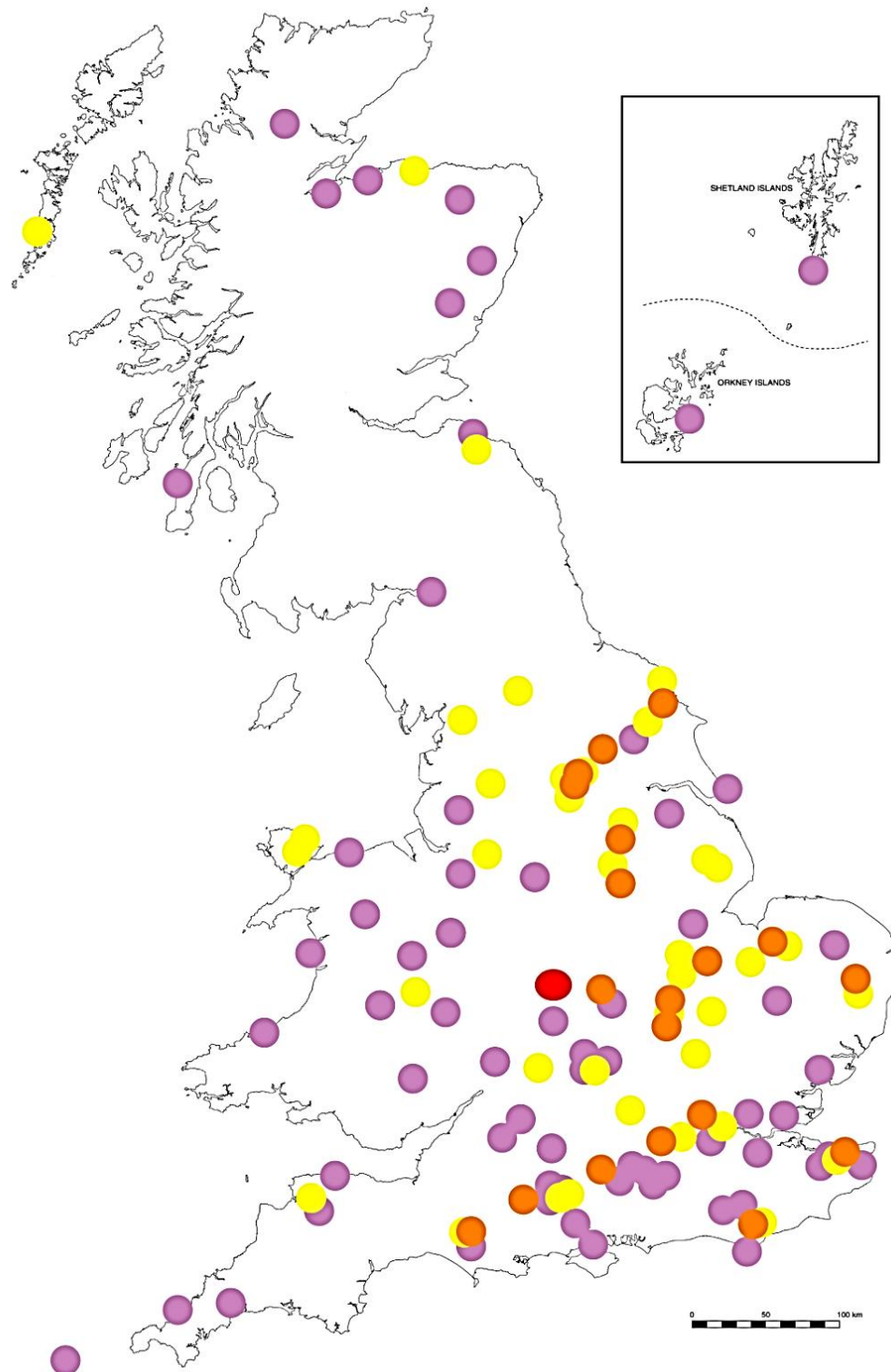


Figure 4.1: Map showing the location of sites providing archaeomagnetic directions in the current British dataset: original data (purple), new data (yellow) and data from the GeoQuest archives (orange). The red marker shows the location of Meriden ( $\gamma = 52.43^\circ$   $\lambda = -1.62^\circ$ ), where all the directions are relocated to (see section 5.2.6 for explanation).

- the reliability of the chronometric placement that has been assigned to each individual magnetic direction.

These two aspects are independent of each other and obtained by completely different methods. It is suggested that the latter aspect, the chronological placement, has been overlooked by previous workers and the associated difficulties underestimated. Therefore, re-examining the dates allocated to each magnetic direction and assessing the reliability of that date would greatly enhance any future SVCs. Arguably, this approach of assessing reliability is highly subjective, so would benefit from ranking the data according to some predetermined criteria. This would enable the correct weighting to be assigned to each data point in any subsequent attempts to model that data. Bayesian statistical modelling applied within such a hierarchical framework (for example, Lanos *et al.* 2005) should enable the benefits of archaeomagnetic dating to be fully realised, but without overlooking its limitations.

There currently exists an algorithm that utilises weighting factors on the input data when estimating a SVC, the RenCurve algorithm (Lanos 2004; section 7.4). This was developed by the archaeomagnetic laboratory at l'Université de Rennes, France, and has quickly become the European standard for constructing regional SVCs. However, this algorithm currently only allows for weighting to be applied that reflects the reliability of the magnetic data, although in future releases it is planned that the reliability of age data will also be accounted for (Lanos pers. comm. 2010). In order to allow comparison with other published European SVCs, the RenCurve algorithm will be applied to the data collected in this study (section 7.6). So that the full functionality of RenCurve could be implemented, it was decided to perform a qualitative assessment of both the magnetic direction and the dating evidence beforehand. Therefore, it was necessary to develop two different ranking systems, one for each aspect, magnetic and chronological. As several different ranking systems have already been applied to the British dataset it was important to review, amalgamate and streamline the results of

previous work. The next section explains all of the information that was collated and provides details of any amendments that were made to the data. The dataset presented in appendix 1 can be divided into three components: meta (this includes general information and archaeological details), magnetic and chronological; each will be discussed in turn.

#### **4.3.1 Meta data**

The first aspect recorded about each of the magnetic directions were details about the name and location of the sampling site. This was broken down into “No.”, “Site name”, “Location”, “Latitude”, “Longitude”, “Site Code”, “Comments (archaeological)” and “Year sampled”. Of these the last three are new additions to the database. The column “No.” contains the data entry reference from the first global database (Tarling 1991), to facilitate any future cross reference or backtracking of data. There were several typing errors in the original dataset with regards to the latitude, longitude and the location of the site sampled, which were corrected. Additionally, if the original site details could not be traced and verified then the co-ordinates of the nearest town or village were used instead. The most extreme example requiring correction was Dan-y-Coed, which was originally input as latitude 55.84°, putting it in western Scotland. However, this site is actually in mid Wales at latitude 51.82°. Most of the corrections to the meta data were purely due to differences in administrative boundaries between regions that had occurred over the past 60 years. One example of this is the site of Ascott-under-Wychwood, as originally this location was listed as being in Oxfordshire but is now classed as being in Warwickshire. This seemingly insignificant difference determines at which Historic Environmental Record Office the site is archived. All locations have now been converted to the World Geodetic System, WGS84, the standard reference coordinate system used by the Global Positioning System and was last revised in 2004. It is also worth noting that, because these data are included in the global data base, the longitude and latitude were only given to two

decimal places and this has not been altered. There was one aspect that caused considerable difficulty, the 16 occurrences of the wrong site name being given in the data base; these are listed in table 4.1. With regards to the other two new categories added, the site code was included in anticipation of the incorporation of any mapping applications, for example with ArcView© or Google Earth©, and where possible the site code allocated by the excavators could prove to be a useful tag, otherwise a simple unique three letter designation was assigned. A further potential use for the site code is to facilitate tracking of the correct details of future excavations in the grey literature. The comment field has been included to provide additional archaeological details on the feature sampled, for example the type of feature or the phase and context numbers, to enable the magnetic direction to be related to the results of the excavation. A final new addition is a field detailing the year the sample was collected.

Site name in original database	Actual site name
Weeping Cross	Sharpstones Hill
Red Hill	Peldon (Site 117)
Harlech	Moel y Gerddi
Rainham	Moor Hall Farm
Stoke-on-Trent	Trent Vale
Long Hanborough	Tuckwell's Pit
Bigberry Hillfort	Bigbury Camp
Ascott	Ascott-under-Wychwood
Hay-on-Wye	Gaer Clyro
Armthorpe or West Moor Park	Gunhills
Probus Bypass	Trelowthas
Methley	Moss Carr
Bury Camp	Bury Wood Camp
Carlisle	Keay's Lane
Bradley Fen	Hanson Brick Quarry
Swineham Quarry	Bestwall Quarry

*Table 4.1: The sites which were listed under incorrect names and the corresponding correct name.*



#### 4.3.2 Magnetic data

The second aspect recorded about each of the data entries refers to details about the magnetic direction. This was broken down into the following: “Inclination”, “Declination”, “ $\alpha_{95}$ ”, “n”, “k”, “Lab Code”, “Magnetic variation”, “Demagnetisation”, “Material Sampled”, “Type”, “Magnetic Rank”, “Weighting”, “Comments (magnetic)” and “Reference (magnetic data)”. The last eight fields are new additions to the database. The “Lab Code”, “Inclination”, “Declination”, “ $\alpha_{95}$ ”, “n” (number of samples) and “k” fields contain the details on the mean magnetic direction (section 3.3 for explanation) at the site location, as presented in the laboratory report after all statistical analysis had been undertaken, but before any relocation had been applied (more details in section 5.2). It was found in a couple of cases that a magnetic direction from the same sample had been entered multiple times. An example is Bigbury Camp; only two samples were collected for this site but the database had four magnetic directions for this site. Essentially, both the original mean direction and the mean direction after the removal of outliers and correction to Meriden had been included. To reiterate, the data presented in appendix 1 show the mean direction at the site location after the removal of outliers, so represents the best estimate of the magnetic direction from that feature. The earliest work had a partial correction for latitude applied to the inclination values, correcting them to London (Aitken 1958; Aitken & Harold 1959; Aitken & Hawley 1966; 1967), which has been removed. The correction to Meriden is a mathematical procedure (Noel & Batt 1990), that can be easily applied, and is currently necessary for calibration purposes, but future research may render this step superfluous, so only the final direction at site location is quoted and also broadens the potential applications of this dataset. The fields: “ $\alpha_{95}$ ” and “k” both contain values pertaining to the precision of the magnetic direction; typically in the UK the “ $\alpha_{95}$ ” statistic is quoted, but in Europe the preferred convention is to quote k, so both parameters are included here for completeness. This difference probably originates from differences in sampling methodology. Where no estimate of k had been quoted in the laboratory report it was calculated using equation 12 given in section 3.3.

Some of the directions have had some corrections applied to them, specific details on what has been done per direction are included in the “Comments (magnetic)” field, which also includes the method used to orientate the samples on site. Generally, Clark (1988) applied an arbitrary correction of 2.4° to all magnetic directions from material sampled from walls. This has not been removed as the magnetic refraction effects it is meant to correct for may be real, but there is growing evidence that this is not the case (Bucur 1994, Tanguy *et al* 2011). Therefore, by noting any directions which may have been affected this information will enable the effect of this correction to be monitored, and if necessary, removed later. Two interesting examples of corrections applied to the magnetic directions that have been highlighted, but are probably necessary, are from Maiden Castle, where corrections for slumping of the hearth material were applied, and Scots’ Dyke, where corrections to take account of the magnetic interference of nearby electricity pylons were added. Where a magnetic compass was used to orientate the samples on site a correction for magnetic variation has also been applied. Finally, a series of fields were added to this section which may facilitate comparison of data points at a later point in this research or for future researchers, these are as follows: “Demagnetisation method”, typically alternating field or thermal demagnetisation; “Type”, this provides details on the recording mechanism, so either TRM or DRM, and if the “Material sampled” is coupled with “Type” it may facilitate the comparison of the reliability of different recording mechanisms in later stages of data analysis. The categories for “Material sampled” are: burnt clay, burnt stone, limestone, silt, and stone, vitrified clay and vitrified stone.

The new field “Weighting” was included to follow the criteria suggested by Chauvin (2000: 133), and is being adopted by other laboratories (Schnepp *et al*. 2009). In section 6.6, the magnetic directions recorded by material fired on a known date were compared to observatory data for the same date. These results highlight the need for some type of quality assessment for each of the data points, which influenced the development of the ranking system for the database. This control is considered

necessary, so that only suitable and high quality data points are included in the construction of any model of geomagnetic SV. The comparison of the magnetic direction recorded via TRM with observatory data, presented in section 6.6, implied that magnetic minerals can consistently capture the ambient geomagnetic field on cooling through their Curie temperature outside tightly-controlled laboratory conditions, but there are caveats, particularly with regards to the precision of the recording mechanism and the stability of the remanent signal, section 3.5. There have been other attempts to qualitatively assess the magnetic data within the British reference curve and the world database (Hamm-Yassi 1983; Tarling 1991), but when examining the data collected during this research, a system was developed that incorporated previous work (table 4.2). These categories only apply to the directional data which is currently the entire British dataset. Current thinking is moving towards using complete vector data to produce a SVC, so would include intensity data (Aidona *et al.* 2006; Schnepp *et al.* 2009), therefore Chauvin's criteria (table 4.3) would be applicable. The last field, "Reference (magnetic data)", contains a reference for the source of the magnetic data; typically this is a laboratory report and for those that it has been possible to obtain the original they are currently archived (electronically) in the archaeomagnetic laboratory at the University of Bradford.

Category	Definition
0	NRM only
1	$\alpha_{95} > 15; N > 1$
2	$\alpha_{95} > 9; N > 1$
3	$\alpha_{95} > 5; N > 8$
4	$\alpha_{95} > 3; N > 8$
5	$\alpha_{95} < 3; N > 8$

*Table 4.2: The ranking system for the magnetic data based on the work of Hammo-Yassi (1983) and Tarling (1991), where 0 represents the most unreliable data and 5 the most reliable. In the current reference curve only data from categories 2-5 are included (Zananiri et al. 2007).*

$W_r$	Method	Cooling rate correction	Anisotropy correction	$W_M$	Material	$W_N$	Number of determinations
6	Thellier or Coe	Yes	Yes	4	Baked clay, bricks or lava flows	6	6 or more
5	Thellier or Coe	No	Yes	3	Tiles	5	5
4	Thellier or Coe	No	No	2	Pottery	4	4
4	Shaw	Yes	Yes	1	Small objects with strong effect of shape: pipe	3	3
3	Shaw	No	Yes			2	2
2	Shaw	No	No			1	1
1	Other	-	-				

*Table 4.3: The weighting criteria defined by Chauvin et al. (2000), which reflect the reliability of the applied palaeointensity technique ( $W_r$ ), the type of material ( $W_M$ ) and the number of palaeointensity results per site ( $W_N$ ). The final weight is  $W=W_r+W_M+W_N$ , so for palaeointensity data the maximum weight is 16 and the minimum is 3.*

### 4.3.3 Chronological data

The third aspect recorded about each of the data entries refers to details about the chronological placement of each magnetic direction. This was divided into two main groupings, the original age estimate and the revised age estimate. Within each of these two groups there were fields containing details on the minimum and maximum age value, the median age with an error estimate in years and a qualitative rank on the reliability of the age range. To date there appears to have been little work done on the dating of the magnetic directions in the British archaeomagnetic database. In most instances a general archaeological period has been assigned, so the problem of assigning a date to the magnetic data has been a major preoccupation of this research. In order to maintain some continuity with earlier qualitative work on the British reference curve, the ranking system employed here is an amalgamation of previous attempts (Aitken & Weaver 1962; Clark *et al.* 1988) and is presented in table 4.4. Also, to maintain continuity with earlier work and clarity for the latter stages of this work, all BC dates are presented as minus values and AD dates as positive, e.g. 100BC is stated in the database as -100, whereas AD100 is 100.

Category	Definition	Example of application
A	Complete confidence	Posterior density estimates or radiocarbon dating of single entity samples from the same sediment/context
B	Reasonable confidence	Radiocarbon dating of associated material from the same feature, stratigraphically related typological dating
C	Doubtful, but worth considering	Typological dating from associated/not stratigraphically related diagnostic artefacts
D	Very doubtful	Typological dating from structural evidence or general date range assigned due to lack of diagnostic material.

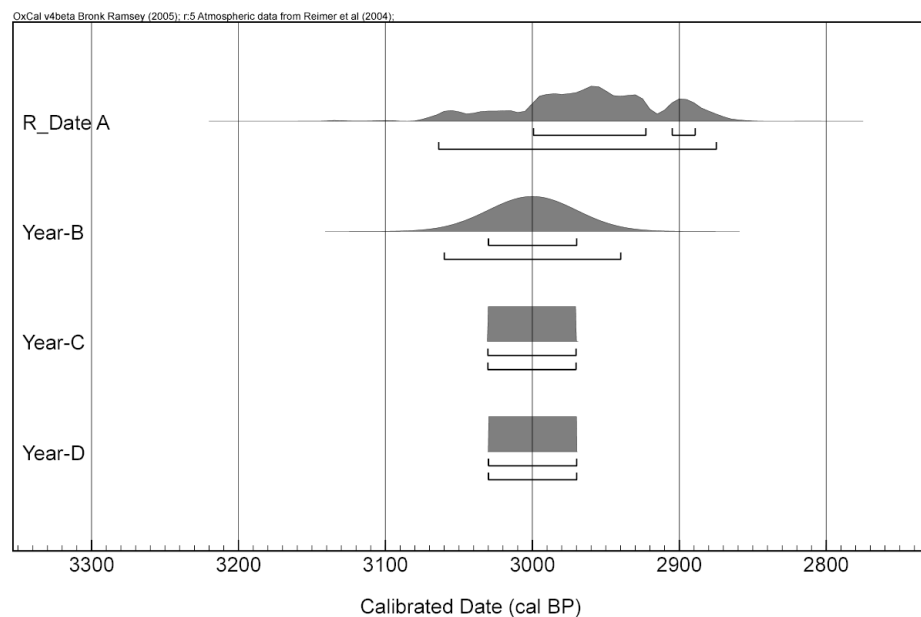
Table 4.4: The ranking system for the dating evidence applied to each of the magnetic directions  
Clark's ranking 1 and 2 correspond to Aitken's A and B respectively (after Aitken & Weaver 1962).

This research is viewed as neither definitive nor comprehensive, so five additional fields have been included in the dataset associated with the revised date range: “Date type”, “Date reference”, “Distribution shape”, “Stratigraphic Relationships” and “Reference (dating data)”. These contain details on how the new age range has been obtained. “Date type” falls into nine categories: “Radiocarbon”, “Event”, “Ceramics”, “Phase”, “Combination”, “Luminescence” and “Architecture”. “Radiocarbon” indicates that either a single determination, or series of determinations, have been utilised to obtain the date. With the former the corresponding laboratory code is provided in the “Date ref” field. Where “Event” is in the “Date ref” field, this indicates that the age range was obtained from a Bayesian model constructed using OxCal 4.1; details of how these are constructed are provided in section 4.5, whereas information on the specific model for each direction, where this was applied, are provided in appendix 2. Regarding the application of radiocarbon determinations, the internationally agreed recommendations for quoting radiocarbon determinations and calibrated radiocarbon dates (Mook 1986) were adhered to and all date ranges quoted are at 95% confidence intervals. In addition, some of the older radiocarbon determinations were originally calculated using the original half-life for radiocarbon of  $5568 \pm 30$  years, which has since been revised to  $5730 \pm 40$  years. For consistency all the BP dates calculated with the old half-life were adjusted to the revised radiocarbon half-life by multiplying the old date by 1.029 (Olsson 1970). Furthermore, all ages quoted have been rounded up to the nearest five year interval. “Luminescence” indicates that either a thermo or an optically stimulated luminescence date was used with more details provided in the “Date ref” field. All luminescence dates are quoted at 68% probability. “Ceramics”, “Typology” or “Architecture” indicates the nature of the archaeological chronological indicator utilised. The corresponding comments in the “Date reference” field are relatively self-explanatory: “Stratigraphically related” or “Not stratigraphically related” refers to the chronological indicator’s relationship to the feature sampled, whereas “Phase” indicates that the date applied to the fired feature was taken from the overall site chronology, as applied by the excavating archaeologist.

This category was generally only applied in cases where there were no chronologically diagnostic artefacts closely related to the feature sampled. "Pending" means that either the excavation or the post excavation work was still on-going and will be discussed further in section 4.7. Finally, a field containing reference details for the archaeological information has been included. Typically, this reference is for the published excavation report for the site sampled and is the source material for the archaeological details used to calculate the estimated date range. Full details on how the date range for each magnetic direction was obtained can be found on a site-by-site basis in appendix 2.

Two important new fields are "Distribution shape" and "Stratigraphic relationships". With regards to "Distribution shape", different types of dating evidence provide date ranges that when represented mathematically provide very different distributions (figure 4.2). Calibrated radiocarbon dates and posterior density estimates provide multimodal distributions and, although these look complicated, they tend to be well-defined mathematically. Luminescence dates are assumed to follow a normal distribution, so again they have quantifiable uncertainties, whereas the date ranges obtained from "Ceramics", "Typology", "Architecture" and "Phase" all have rectangular or uniform distributions, which look simple but are actually poorly defined. The date ranges obtained from classical archaeological evidence, typically ceramic typologies, are also all fairly subjective and open to revision. Even so, many of the ceramic typologies or nuministics with their associated estimates of dates developed through archaeological study, are now well established and appear fairly robust. These differences, in how estimates of age from different sources are represented mathematically, are an important point that has been disguised by the apparently innocuous and precise format that each date appears in the database. Typically the age has taken the form of a date in calendar years with a plus or minus value, also in calendar years. Examples from the database are:  $80 \pm 10$  or  $-55 \pm 90$ . The former appears more precise, but it is based on a ceramic sequence so has a uniform distribution,

which is mathematically speaking more uncertain, whereas the latter is based on Bayesian analysis of a suite of radiocarbon determinations, so is actually much better defined. It is beyond the scope of this research to develop a method to deal fully with these uncertainties, although section 7.4.2 outlines some beginnings. This is a potential issue that, if unaddressed, may hinder the development of the future archaeomagnetic SVCs and other researchers are currently working on addressing this problem (Bronk Ramsey and Lanos pers. comm. 2010). Therefore, it is hoped that any attempts made here to identify these issues should facilitate their work.



*Figure 4.2: A series of likelihood distributions; these examples all centre on 3000BP and demonstrate how the age estimates from different types of dating evidence are defined mathematically (Bronk Ramsey 2008b: 44 figure 1). Year A is the multimodal distribution, typical of calibrated radiocarbon dates; Year B is a normal distribution, typically associated with thermoluminescence dates; Year C is a uniform distribution, where just an age range is given, typical of typological dating and finally Year D is another type of uniform distribution where the probability is defined by the central point and half width, for example nuministics dates.*

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Finally, to make the most of all of the available data, details on the stratigraphic relationships were also included. These refer to the relationships between individual structures or features sampled for archaeomagnetic studies. It is currently possible to incorporate information from stratigraphic relationships into the RenCurve algorithm (Lanos 2004) and this has been successfully implemented to good effect at a medieval site in Lübeck, Germany (Schnepp *et al.* 2009). So, following the German case study, the precision of the associated age ranges from several sites have been augmented by including details on the stratigraphic ordering of the features (section 7.4.2).

#### **4.4 Method for reassessing the archaeological age estimates**

In order to determine the impact of the reassessment process, initially all of the original data were qualitatively assessed using the ranking system presented in tables 4.2 and 4.4. Then the revised date range associated with each archaeomagnetic data point was re-assessed in turn. This presented a massive task, so the reappraisal of the collated archaeomagnetic data commenced with sites that had been excavated recently and had more than one magnetic direction, as they have the most scope for refining the date ranges assigned to the archaeomagnetic directions. Of the 98 sites, Old Scatness provided the most directions in the current reference curve (22) so was utilised to develop the methodology to re-assess the chronological placement of the magnetic directions from archaeomagnetic data (section 4.6.1). Then the qualitative ranking system for the magnetic data was employed to prioritise the rest of the dataset, with the initial focus on those data points that had the best magnetic data, i.e. ranks 4 and 5. This next section will describe the problems that needed to be overcome, the procedures developed to address them and three case studies to illustrate how they were applied.

#### **4.4.1 The problem**

Basically, any archaeomagnetic SVC is composed of magnetic directions obtained from archaeological sites, which have been allocated an estimated date range derived from the associated archaeological evidence. As the British reference curve was initially compiled by geophysicists, most of the magnetic directions from Iron Age sites have been given the generic date range 700BC-43AD because they have been defined as “pre-Roman Iron Age”. Consequently, the temporal assignments of many data points were ill defined with little confidence in their reliability (Clark *et al.* 1988). In order to address this issue the archaeological evidence associated with each archaeomagnetic direction in the British reference curve was reviewed. It was believed that a critical re-evaluation of the available archaeological evidence, and the conscientious application of scientific dating from each site, would enable the age range associated with most data points to be reduced.

#### **4.4.2 The procedure**

Having identified this problem with the current SVC, the question remained as how to provide an independent date for each of the magnetic directions when they are recovered from a Bronze Age or an Iron Age site and produce a realistic measure of the errors associated with that date? This presented a complex issue, particularly as it was essential to provide a rigorous and transparent methodology that avoided any tautological or circular arguments. For example, it was particularly important that the dates are obtained in a manner that was independent of the archaeomagnetic date ranges provided by previous SVCs (Aitken 1958; Aitken & Harold 1959; Aitken 1960; Aitken & Weaver 1962; Aitken *et al.* 1963; Aitken & Hawley 1966; 1967; Clark *et al.* 1988; Zananiri *et al.* 2007). At the same time, the archaeological record should inform the date ranges, so the dates do not conflict with the stratigraphy of the sites from which the archaeomagnetic directions were obtained.

It was decided that the best approach was to employ all of the available evidence from each site that had undergone archaeomagnetic dating, i.e. the archaeology and all potential sources of dating from the associated archaeological assemblage. Therefore, the typological sequencing of structural forms or artefacts, nuministics, stratigraphic relationships and other scientific methods of dating would be considered. This was a colossal undertaking so, following the approach suggested by Armit (1991), the potential dating methods were placed into a hierarchy which reflects the reliability of each of the methods. Therefore, scientific methods of dating (for example radiocarbon dating) and stratigraphic relationships were considered above all other methods. Moreover, given the problems associating a date obtained from a scientific method of dating and the actual archaeological event of interest (Taylor 1987: 15), scientific dates were only used in two circumstances. These are that either the scientific date can be directly related to the same event that caused the geomagnetic field to be recorded, or that a sequence of scientific dates and their stratigraphic relationship to the archaeomagnetic direction are available. Only if no scientific dates were available would the other methods be introduced, in the following order: nuministics, typological sequencing of artefacts and structural forms. Coins can only provide *terminus post quem*s but can potentially provide smaller age ranges than typology and in turn the age ranges associated with artefacts are generally smaller than those allocated to architectural developments. It was deemed necessary to utilise all of the available dating evidence in a transparent methodology, accessible and familiar to archaeologists, so Bayesian modelling was employed. As this is fundamental to the approach used in this research, the principles underlying Bayesian models will be outlined before continuing with the explanation of the methodology.

#### *4.4.2i Bayesian logic and its application*

An interesting yet often overlooked point is that many archaeological dating regimes appear to focus on providing independent dates, or collaborative dating evidence for artefacts, rather than the construction and lifespan of structural elements

or the use of an entire site. The reason for this is probably because dates for artefacts are more readily transferable to other assemblages. However, this can be overcome by the application of Bayes theorem (1763) to the information provided by archaeological data, as it enables knowledge regarding the order of archaeologically identified events, or phases of activity provided by the stratigraphic record, to be taken into account when calibrating radiocarbon determinations and/or sequencing artefacts recovered from the archaeological record (Buck *et al.* 1996). The basic premise behind the introduction of a Bayesian approach to archaeological interpretation was that by incorporating archaeological information on the relationships between the events under consideration, with the results from calibrating radiocarbon determinations, it would instil greater confidence in the results of the calibration process and enable a series of radiocarbon determinations to be calibrated together (Buck *et al.* 1991). This approach was later expanded to serve another purpose, namely identifying which of several possible interpretations of archaeological data is the most likely to have actually occurred (Buck *et al.* 1992; Buck *et al.* 1996 chapters 10 and 11; Bayliss & Bronk Ramsey 2004). Therefore, if applied critically, it is possible to identify which of two or more possible general explanations generated the archaeological record revealed by excavation (for example Needham *et al.* 1997). The aim of this section is not to describe the processes behind this method of statistical modelling, as this is covered elsewhere (Buck *et al.* 1996 particularly chapters 2 through 5); instead, it is to explain the logic behind the application of Bayesian modelling, as applied in this research.

Statistics is a branch of applied mathematics concerned with the collection and interpretation of quantitative data and the use of probability theory to make predictions. Bayesian statistics are concerned only with the probability of a certain hypotheses being true, or more specifically the more likely to have occurred. Bayes theorem (1763) (equation 14) is the basis on which prior information (details that were already known before data collection) and the data collected, are combined in a logical

manner to give the posterior information (an interpretation of the data given the prior information). This sounds complex but thinking in terms of Bayesian models can be made more accessible through an example frequently encountered during the fieldwork aspect of this research. In order to collect new archaeomagnetic samples for this research it was necessary to travel to sites across the country. Generally, the aim was to arrive around 9:00am to give the site supervisor chance to set up the site for the day. When planning the journey to an archaeological site, use was made of Google Maps© to plan the route and to provide an estimated journey time. In this case the prior beliefs are the map and associated details on the speed limits for these roads built into Google Maps©. The data are the starting point and the destination, which can be modified to request that the shortest or quickest routes are calculated. The posterior belief therefore is the route and the estimated journey time provided by Google Maps©.

When applying Bayesian statistical analysis to archaeological information the archaeological interpretations of the site are referred to as models, which are essentially a simplified representation of the formation processes that led to the development of the archaeological sequence. Stratigraphic relationships, the understanding of the phases of use at an archaeological site and the radiocarbon calibration curve are the prior beliefs; they represent information that was already known, albeit with varying degrees of certainty. Indeed the process of using prior information is actually common to archaeologists, if unrecognised, as they routinely use prior beliefs about known Iron Age sites to identify a new site as Iron Age. However, when these prior beliefs are applied to a Bayesian model, they are quantified by attaching levels of certainty in those beliefs. Typically, the prior beliefs are the stratigraphic relationships between the data points; for example, event A happened before event B, event C may have happened at the same time as B, but event D definitely happened after events A, B and C. The data are generally the radiocarbon determinations, but other dating evidence can be included, and this dating evidence is

placed in its correct location within the stratigraphic matrix. Therefore, the posterior information is the interpretation of the data, given the prior understanding. For the most common archaeological application of Bayesian statistics, the posterior belief is the most probable calendar date range for each archaeological event represented in the stratigraphic sequence. This relationship between the posterior density, the likelihood and the prior density is expressed formally by Bayesian theory as:

$$p(\theta|x, \tau) = \frac{p(x|\theta, \tau)p(\theta)}{\int p(x|\theta, \tau)p(\theta)d\theta}$$

Equation 14

When applied to the understanding of dating evidence recovered from archaeological sites,  $\theta$  is the unknown calendar dates  $\theta_1, \theta_2... \theta_n$ ,  $x$  represents the data, typically radiocarbon determinations  $x_1, x_2...x_n$  and  $p(\theta)$  represents the prior probability of the unknown calendar dates. Full details on the mathematics underlying these Bayesian models, as they are applied to archaeological problems, have been discussed extensively elsewhere (Bronk Ramsey 1995; Buck *et al.* 1996; Buck & Millard 2004), so will not be repeated here, and despite some initial doubts (for example Reece 1994), this approach is now generally accepted, if not widely understood. The main benefit of this approach has been to provide a formal framework that allows both absolute and relative chronological information to be integrated in a coherent way. However, it is worth reiterating that there are differences between how age estimates from different methods of dating are defined mathematically, since all non-scientific dating methods provide rectangular distributions (figure 4.3). Although this may appear to complicate the Bayesian model this difference actually provides a clearer representation of the available chronological information. As mentioned above, this problem also applies to any attempt to construct a SVC and will be returned to in section 7.3.

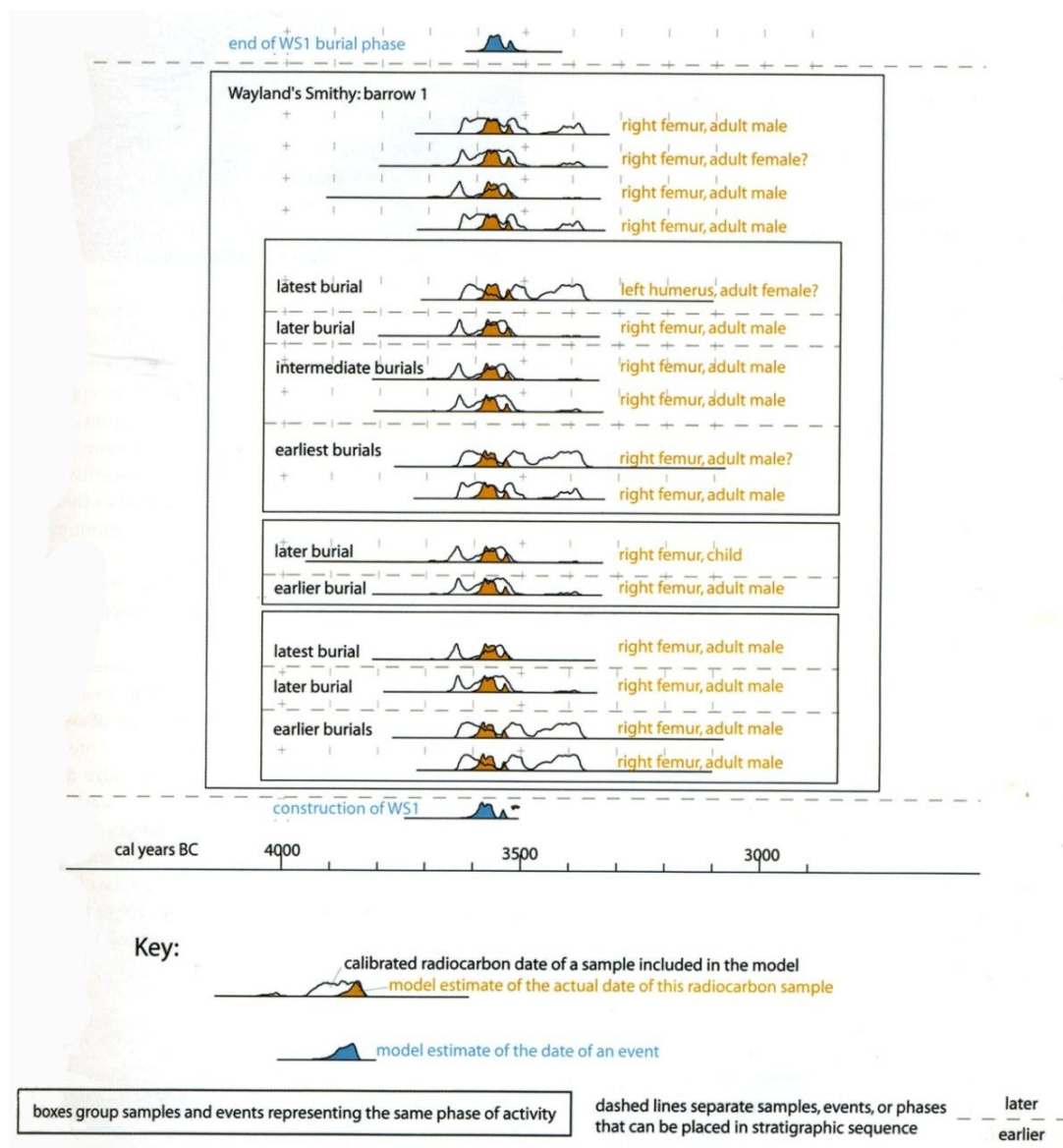


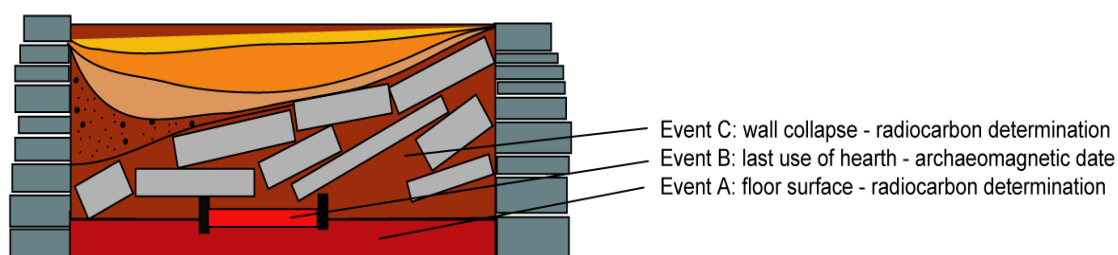
Figure 4.3: An illustration of how Bayesian analysis of a series of date ranges can enable any particular date range to be constrained by all of the other dating probabilities in the sequence. This example is from Wayland's Smithy II (Bayliss et al. 2007: 19). Essentially, Bayesian theory enables a mathematical relationship to be created between the stratigraphic information and the dating probabilities in the sequence; this enables a different (typically but not necessarily smaller) estimate of the possible date range for each individual dated event to be produced. © English Heritage (image produced by John Meadows), reproduced with permission.

The reason for adding the probabilities can be made more intuitive by returning to the travelling metaphor. All journeys vary; sometimes everything runs smoothly and it is possible to arrive earlier than expected or sometimes things can go wrong, for example poor weather conditions or vehicle trouble, which can lead to a later than intended arrival time. In order to account for these possibilities and so create a more realistic model, statisticians can include an estimate of error, which gives rise to probability distributions. Therefore, the prior and posterior beliefs are often stated as probabilities. For example, again keeping with travelling, a bus timetable would be more precise if each entry contained an estimate of the error associated with each bus arrival time, for example  $08:10 \pm 15$  minutes, if it is during rush hour, or  $14:30 \pm 3$  minutes for quieter times of day. This information can also be expressed in statistical terms as the probability of Y (the known likelihoods represented by the planned route and method of travel), multiplied by probability of Z given Y (this represents the prior beliefs and in this case is represented by the information from road maps), which equals the probability of Y and Z (this is the posterior belief of the time taken to make the journey).

Returning to the procedure developed to provide an independent date for each of the magnetic directions, this is a process that in recent years has been made widely accessible through the production of a variety of freely available online programs, that can be run on personal computers with an internet connection, for example OxCal (<http://c14.arch.ox.ac.uk/oxcal/>), BCal (<http://bc1.shf.ac.uk/>) or CALIB (<http://calib.qub.ac.uk/calib>). All of these programs essentially provide an interface which enables the user to either calibrate a radiocarbon determination, in a manner that takes account of the nature of the calibration curve, or to build up sophisticated statistical models that recreate a simplified version of the archaeological sequence (for BCal see Buck *et al.* 1999; for OxCal see Bronk Ramsey 2001 and for CALIB see online manual), depending on the individual requirements of a given situation and the amount of data available to the user. Basically, the user can construct Bayesian models



that represent the prior knowledge provided by the site stratigraphy and also incorporate the archaeologist's interpretation of the archaeology via phasing. Therefore, when radiocarbon determinations are included within this Bayesian model and then calibrated, the resultant age estimates are constrained by the prior knowledge which is not only the nature of the calibration curve, but also the archaeological relationships. The simplest scenario is three events: Event A happened before Event B and both A and B occurred before Event C. An archaeological scenario that follows this pattern is represented pictorially in figure 4.4.



*Figure 4.4: A sequence of archaeological events A, B and C. We know that event A is earlier than B and both A and B are earlier than event C. If events A and C are dated, applying Bayesian theory means it is possible to calculate the most probable age range for event B.*

The main difficulty with the application of Bayesian models in archaeology is that these programs contain generalised assumptions about the reliability of the prior information, which may not be applicable to every stratigraphic sequence, mainly that the value of  $p(\theta)$  and the assumed temporal distance between each value of  $\theta$  is fixed. It is likely that the time elapsed between Events A and B was probably fairly short, whereas the amount of time that passed between Events B and C was much longer, but this is almost impossible to derive from the archaeological record. This means that it was necessary to weigh up the convenience of using a generic model, against the benefit of creating a model that actually reflects current understanding of the

archaeological record for each individual site. Where possible, every attempt was made to tailor the generic models available to the specifics of the existing archaeological information. This can be explained by returning to the example of travelling to site given above; in order to arrive on schedule it is necessary to have an accurate estimate of the journey time, so that it is possible to calculate when to set off. Here there are many variables to be taken into account that the Bayesian algorithm in Google Maps© does not allow for, including: the time of day that the journey is being undertaken and consequently the chances of being caught in commuter traffic, the weather conditions, the distribution of road works or local schools, or the location of any recently installed traffic calming schemes. It is here that local knowledge can prove invaluable. For a site visited in the Greater Manchester region, a slightly revised route to that proposed by Google Maps© was taken due to personal knowledge on the condition of the local roads and main commuting routes. In a similar manner, the principal archaeologist excavating the site was seen as being an invaluable source of information that would only aid any reassessment of age estimates. Therefore, local knowledge was considered to be of immense importance to the application of this approach in this research and is discussed further in section 4.5.1.

#### *4.4.2ii Summary explanation of the procedure for reassessing the archaeological age estimates*

As described in section 2.5, the British archaeomagnetic reference curve has undergone a series of developments. So, in order to avoid circular arguments by referring back to the dates provided by earlier calibration curves, it was deemed necessary to attempt to provide a completely independent, yet reliable, date for each of the magnetic directions selected for reanalysis. As each heated feature can be clearly related to a structure and the life span of a building represents an obvious unit of time, Bayesian logic was applied to provide an independent measure of when each heated feature was last used, in one of two ways:

1. The most straightforward case was if the hearth was directly dated by another method. An independent date, available from the same context sampled to provide the magnetic direction, was used to directly date the last burning event. This method was applied with caution, as predominantly the independent dating method involved will be radiocarbon, so the material sampled needed to be a short-lived single entity, for example a charred barley grain, and other criteria for assessing the reliability of radiocarbon determinations were also observed (Ashmore 1999).
2. If the hearth could not be dated directly, then the location of the last use of the hearth was identified within the stratigraphic record and the associated date range applied. This could be the date range for a phase of activity, as identified by the excavating archaeologist or by querying a Bayesian model of the entire site. As the models were defined by the stratigraphic sequence, as identified by the archaeologist, they could provide posterior density estimates for an undated event identified in the sequence by taking into account the restrictions imposed by the rest of sequence (Buck *et al.* 1996 chapter 7). Where possible, the age range that should be assigned to the magnetic direction from each hearth will be calculated to within 95% probability (figure 4.3).

It is necessary to add a caveat to this methodological approach. If scientific dating was available and either no stratigraphic relationships were available, or the date cannot be directly related to the event that recorded the archaeomagnetic direction, then it will be flagged up as problematic. The reasoning is that of the types of scientific dating applicable to the first millennium BC (radiocarbon, dendrochronology, optically stimulated luminescence and tephrochronology), radiocarbon is probably going to predominate, but its application during this period is restricted by the lack of precision in the Iron Age (Haselgrove *et al.* 2001), specifically the period between 700-400BC where the radiocarbon calibration curve provides low resolution (Reimer *et al.*

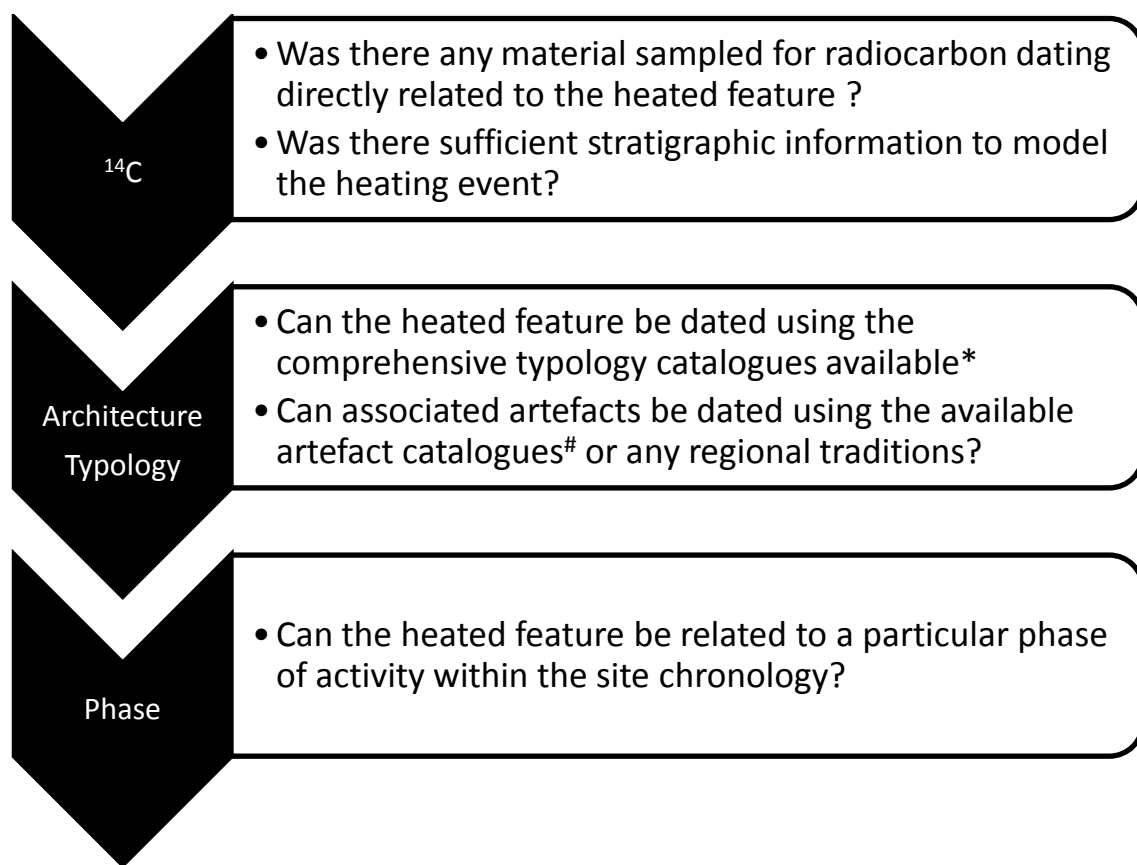
2004; Bronk Ramsey 2008a; Reimer *et al.* 2009). The implication is that the age ranges provided by individual calibrated radiocarbon determinations may be of comparable size, or larger, than the currently allocated date. However, the size of the date range is not considered to be the greater problem; rather, it is considered to be the occurrence of large age estimates with no appreciation of the relationship of the source of the age estimate to the event of interest.

The main purpose of reappraising the dating evidence was to provide more reliable estimates of the date ranges, which would not be achieved unless a scrupulous approach was adopted. It was considered preferable that a lack of appropriate dating is flagged up for a selection of archaeomagnetic determinations, via the ranking system discussed in section 4.3.3, and that any particular date range remains unchanged or a larger age estimate is allocated, rather than the application of a poorly reasoned association in order to produce smaller age ranges. It was hoped that the ranking system would enable a balance to be achieved, by placing less importance on the archaeomagnetic directions with unreliable date ranges when the SVC is reconstructed.

#### **4.5 Application of the method for reassessing the archaeological age estimates**

As discussed above, all methods of dating were considered and applied to the problem of dating the last use of all of the heated features represented in the database. Every attempt was made to ensure that this was done critically, with a consistent awareness of the limitations of the available dating evidence. Throughout this process, the main concern was to ensure that the date range allocated to each of the magnetic directions provided a more accurate reflection of the associated archaeology. At this point, the precision of the date range was a secondary concern and it is stressed that the results of this re-evaluation are not considered to be final or absolute. In most cases the observations made by the lead archaeologist were not disputed, but were just included in the British archaeomagnetic database for this first

time. Figure 4.5 is a schematic that shows the general thought processes undertaken as the dating evidence was reviewed. It is hoped that when coupled with the qualitative ranking systems, this method of allocating estimated date ranges to each of the magnetic directions is both transparent and traceable, which should facilitate any future attempts to update or revise this dataset.



*Figure 4.5: A flow chart showing the process by which the available dating evidence was reviewed. \*(sources consulted are: Cleere 1972; Morris 1979; Swan 1984) #(examples used include Hull & Hawkes 1987; Greene 1992; Tyers 1996; Tomber & Dore 1998).*

#### **4.5.1 Ethical considerations**

Before moving onto the case studies, it was felt necessary to explicitly state that only the date assigned to each feature sampled for archaeomagnetism was being

re-evaluated, not the date range for either individual phases or the entire site from which the feature originated. All the interpretations offered in appendix 2 defaulted to the excavating archaeologist's original interpretation and the advice of the principal archaeologist was sought if anything was unclear, where it was possible to track them down. This effort was felt to be necessary, as often the excavating archaeologist's interest in dating is with a view to developing a narrative for the entire site. In contrast, the focus of this research was very narrow, namely on estimating the point in time which a single feature went out of use. These fundamental differences in approach meant that often it was beneficial to discuss how the original data collected were being used and to make sure that the results from this research did not contradict the archaeologist's interpretations of their site. Furthermore, this research could warrant further review in another fifty years time, to maintain consistency with the evolving understanding of Iron Age archaeology. The main point of the methodology developed for this research was to make the most of the available information for each of the sites, which included the opinions of those who excavated them. As it was impossible to become proficient in all aspects of British Iron Age archaeology, this research relied heavily on the experience and expertise of many archaeologists, professional, amateur and academic. Returning again to the example of getting to site on time (section 4.4.2), the importance of local knowledge was not overlooked, as it was felt important to take full advantage of the nuances in the regional variations in the British dataset, as highlighted in section 2.2.

#### **4.6 Case studies**

Three examples have been chosen as case studies to demonstrate the re-evaluation methodology, and highlight its flexibility and limitations. Firstly, the sites of Ferrybridge and Old Scatness have been chosen as typical examples and to conveniently demonstrate the two main uses of the available archaeological information. Estimating a date of last use for the heated feature at Ferrybridge relied

on typological dating of associated artefacts, whereas at Old Scatness more sophisticated statistical models were developed to make the most of the abundant radiocarbon dating. For both sites the common element of the stratigraphic record was used to combine all of the available chronological indicators to answer a single question: when were each of the hearths sampled for archaeomagnetic dating last used? The focus on this aspect is because it is the event that is dated by archaeomagnetic dating. The third case study deals with a class of structures, the vitrified hillfort. These enigmatic structures have been treated separately because they present a unique problem that was not encountered with any other heated feature examined during the course of this research. Vitrified hillforts were chosen as they very clearly highlights the difficulties encountered in attempting to date the last time a heated feature cooled down. The methodology outlined above requires clear identification of the point in time that the event of interest occurred, in relation to the rest of the activity at the site, before any attempts are made to apply the other available dating evidence.

#### **4.6.1 Case study 1: Old Scatness**

The site at Old Scatness was chosen as a case study to explore the potential to reappraise the temporal assignment to magnetic directions, because 22 magnetic directions from the site at Old Scatness are currently in the archaeomagnetic database, with the same broad age range of  $329\text{BC} \pm 371$ , due to a misinterpretation of the archaeological details from this site by Zaneniri and co-workers (2007), which was completely understandable given the complexity of this site and that at the time of compilation the excavations at Old Scatness were still on-going. Therefore, it was decided that, since excavations were now completed, it should be possible to improve on the current situation. A general observation of archaeological dating regimes, as applied to prehistoric sites, is the apparent focus on providing independent dates for artefacts, rather than the construction and lifespan of structural elements. This is

probably because dates for artefacts are more readily transferable to other assemblages. Old Scatness provides a notable exception to this generalisation because there has been an emphasis on obtaining dates for construction (Dockrill *et al.* 2006). Furthermore, this site has the following attributes:

- it provides a long sequence of continuous occupation, spanning at least two millennia, which includes the first millennium BC;
- it provides 28% of the magnetic directions in the current reference curve up to 0AD;
- all of the magnetic directions have been allocated the same age range, 700BC-43AD, so it is highly likely that any attempt to review the dates will yield a positive result;
- it has been subjected to a large-scale open area excavation, meaning that stratigraphic relationships between features have been identified;
- it was a long-term research excavation with an extensive primary archive, that is readily available to the researcher;
- it is arguably the most comprehensively dated archaeological site in the UK.

Therefore, data from Old Scatness represent an ideal situation to investigate the impact of this type of analysis. The key point of the analysis was to improve the date ranges in the Zaneniri *et al.* (2007) database, because these data are also included in the International Geomagnetic Reference Field, CALS7xK, which is a global geomagnetic field model, that provides a description of field behaviour back to 5000BC (Korte & Constable 2008; Korte *et al.* 2009). A review of the dates associated with each of these magnetic directions could potentially have a significant impact on our understanding of secular variation of the geomagnetic field, beyond the ability to date fired features from the first millennium.



The site of Old Scatness is a multiperiod settlement mound, located at the southern end of mainland Shetland, that was first discovered in 1975 during the construction of an access road for the local airport (Dockrill 1998). The collection of over 150 scientific dates from Old Scatness during the course of excavations (the Old Scatness archive; Outram 2005; Outram & Batt 2010) and the development of a comprehensive recording system (Dockrill *et al.* 2009), has enabled the full significance of the resulting independent dates to be realised. During the course of the excavations around sixty hearth features were sampled for archaeomagnetic dating, but not all produced useable results, the most common issue being the redeposition of ash material. In this survey a total of forty-four magnetic directions were examined to determine if they could be dated independently of any archaeomagnetic reference curve and so demonstrate the validity of the procedure outlined above. The excavations at Old Scatness are now completed after over a decade of fieldwork, but during the course of this research only the archaeology relating to the Pictish and Viking settlement was finalised (Dockrill *et al.* 2010), therefore much of the work presented in appendix 2 is based on the author's understanding of currently unpublished material from the Scatness archives and may be subject to future reinterpretation.

The dating evidence associated with all of the hearths sampled was re-evaluated; full details for each hearth are presented in appendix 2, but details on the thirty-six whose associated date range has been altered are summarised in table 4.5. Three hearths could not be included (AM15; AM63 and AM65) because the radiocarbon determinations associated with these features had not been returned in time for inclusion and others were excluded as the material sampled was redeposited. It was found that prudent use of the stratigraphic record and associated dating evidence enabled date ranges to be assigned to 36 of the magnetic directions from Old Scatness, that were independent of any of the previous reference curves. It is worth pointing out that the majority of these features are later Iron Age in the long

chronology utilised in Scotland (table 2.1), therefore they actually relate to the first millennium AD. Perhaps, more importantly, each of these new ranges are a substantial improvement on the date ranges from the current reference curve (Zananiri *et al.* 2007) and more accurately reflect the archaeological record from which they originated. Furthermore, it was discovered for many of the hearths that there was some agreement between the date ranges provided by previous work (Outram 2005), using an earlier curve (Clark *et al.* 1988) and those derived by this research. This comparison, between the new date ranges with the ranges obtained from an earlier calibration curve, was a method of determining how well the system of applying Bayesian logic to the suite of dates from Old Scatness performed. It also provided an indication of the reliability of the calibrated date ranges obtained from the earlier “Clark” curve (1988). One major improvement, due to the use of Bayesian models, is that only one likely age range was produced. The dramatic nature of the improvement to the associated date range is best viewed graphically (figure 4.6). Declination values were selected for display as they showed a greater variation in values than inclination, so any patterning would be more obvious, and a clear pattern is starting to emerge in the revised dataset. There is a small rise and fall in declination around 1AD, followed by a gradual sweep upwards towards the end of the first millennium AD. Old Scatness perhaps represents an idealised situation, but this case study was particularly important as it demonstrated both the viability of the proposed methodology and that the tools necessary to apply this method already existed in OxCal 4.1, a widely used and well-established program. Finally, it should be possible to constrain the date ranges given in table 4.5 and appendix 1 further, by including details of the stratigraphic relationships of the sampled features in a similar manner to that carried out at Lübeck, Germany (Lanos 2004; Schnepp *et al.* 2009). Many of the structures at Old Scatness showed evidence for prolonged occupation, with evidence for two or more floor levels and associated hearths in sequence. These stratigraphic details were included so that they can be utilised in future SVCs, (section 7.4.2), so the actual age estimates for 33

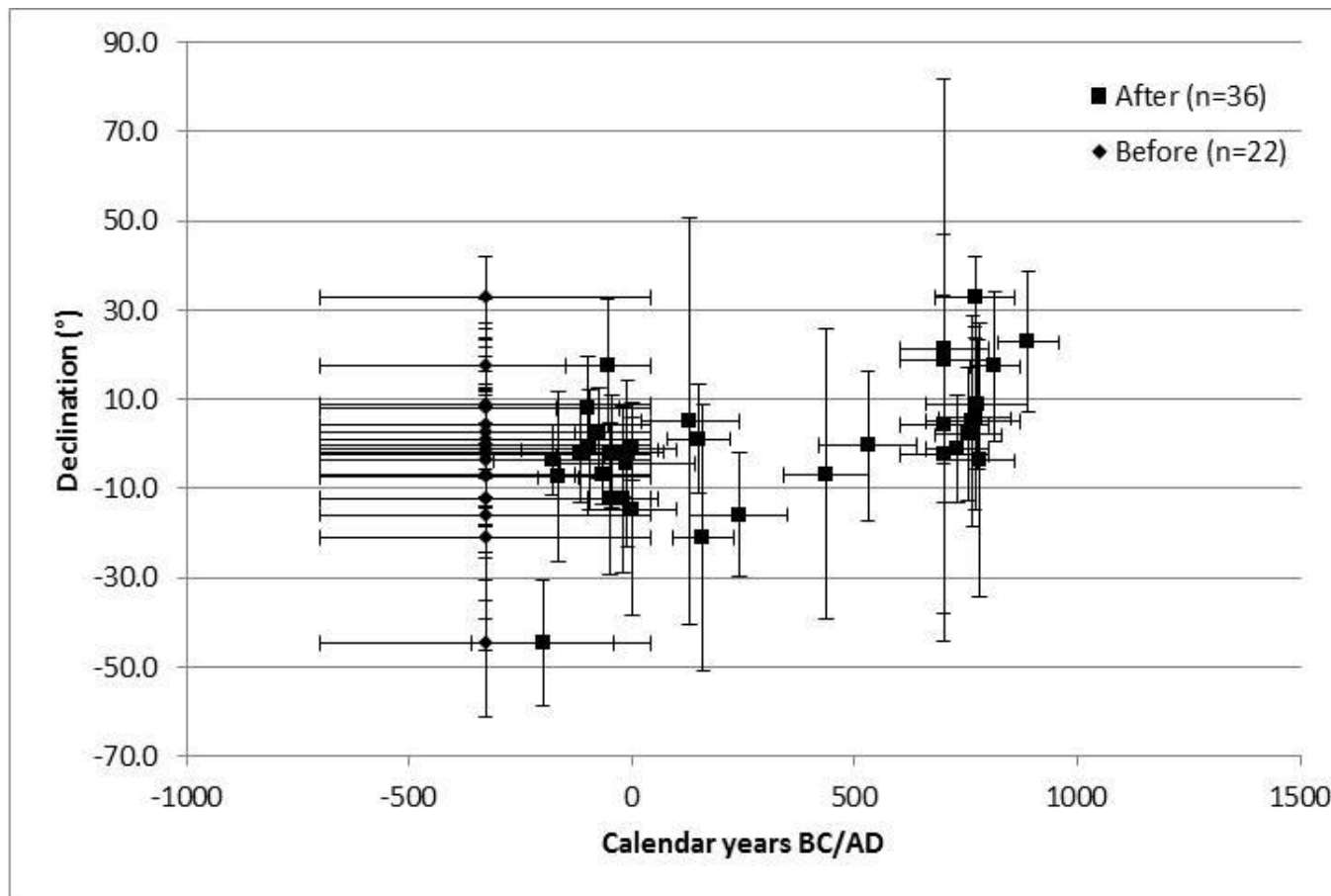


Figure 4.6: Graph demonstrating the impact of applying the methodology devised in this study to the data from Old Scatness. This shows the dramatic difference between the date ranges shown by the x error bars before (diamonds) and after (squares) re-evaluation. The 22 directions in Zananiri et al (2007) had been allocated the same age range of 700BC-AD43. Now their associated age estimates are more recent and smaller. The declination errors were calculated using  $\alpha_{95}/\cos(\text{Declination})$ .

<b>Magnetic direction</b>	<b>Structural form (number)</b>	<b>Previous date range</b>	<b>Revised date range</b>	<b>Origin of revised date</b>	<b>Impact</b>
AM3	Cellular (5)	New data	AD600-800	Architecture	None
AM7	Wheelhouse (6)	New data	AD685-775	Event	None
AM8	Wheelhouse (11)	New data	AD875-1025	Event	None
AM11	Wheelhouse (11)	New data	AD870-1020	Event	None
AM12	Wheelhouse (6)	New data	AD680-760	Event	None
AM14	Wheelhouse (6)	New data	AD630-765	Event	None
AM16	Cellular (19)	New data	AD675-995	Event	None
AM19	Cellular (7)	New data	AD600-800	Architecture	None
AM21	Sub rectangular (15)	New data	115BC-AD130	PDE	None
AM22	Aisled roundhouse (14)	New data	105BC-AD75	Event	None
AM23	Aisled roundhouse (14)	New data	105BC-AD75	Event	None
AM24	Cellular (7)	700BC-AD43	AD600-800	Architecture	None
AM27	Wheelhouse (11)	New data	AD810-950	Event	None
AM29	Sub rectangular (8)	700BC-AD43	190-20BC	PDE	Smaller range
AM30	Wheelhouse (11)	700BC-AD43	AD720-885	Event	Smaller range, later
AM32	Cellular (20)	700BC-AD43	AD665-835	Event	Smaller range, later
AM33	Aisled roundhouse (14)	700BC-AD43	140-15BC	Event	Smaller range
continued					

<b>Magnetic direction</b>	<b>Structural form (number)</b>	<b>Previous date range</b>	<b>Revised date range</b>	<b>Origin of revised date</b>	<b>Impact</b>
AM34	Long piered roundhouse (21)	700BC-AD43	AD260-530	PDE	Smaller range, late
AM35	Amorphous (22)	700BC-AD43	165BC-60AD	PDE	Smaller range
AM36	Long piered roundhouse (23)	New data	AD25-235	PDE	None
AM38	Sub rectangular (8)	700BC-AD43	190-20BC	PDE	Smaller range
AM40b	Aisled roundhouse (12)	700BC-AD43	90BC-AD20	Event	Smaller range
AM25&42	Long piered roundhouse (21)	700BC-AD43	AD330-545	Event	Smaller range, later
AM43	Long piered roundhouse (21)	700BC-AD43	AD30-235	Event	Smaller range, later
AM45	Wheelhouse (11)	700BC-AD43	AD720-885	PDE	Smaller range, later
AM46	Aisled roundhouse (12)	700BC-AD43	90BC-AD20	Event	Smaller range
AM47	Aisled roundhouse (14)	700BC-AD43	140-15BC	Event	Smaller range
AM48	Cellular (7)	700BC-AD43	AD600-800	Architecture	Smaller range, later
AM50	Long piered roundhouse (21)	700BC-AD43	25BC-AD325	Event	Smaller range, later
AM52	Aisled roundhouse (12)	700BC-AD43	265-20BC	Event	Smaller range
AM53	Amorphous (22)	700BC-AD43	165BC-AD60	PDE	Smaller range
continued					

Magnetic direction	Structural form (number)	Previous date range	Revised date range	Origin of revised date	Impact
AM56	Long pierced roundhouse (21)	700BC-AD43	25BC-AD325	Event	Smaller range, later
AM57	Corbelled cell (24)	700BC-AD43	850BC-AD120	Event	Larger range
AM58	Aisled roundhouse (14)	700BC-AD43	220-40BC	Event	Smaller range
AM60	Aisled roundhouse (12)	700BC-AD43	265-20BC	Event	Smaller range
AM61	Aisled roundhouse (14)	700BC-AD43	310-50BC	Event	Smaller range

*Table 4.5: Summary results from re-evaluating the dating evidence associated with each of the hearths sampled for archaeomagnetism at Old Scatness. PDE = posterior density estimate.*

out of 36 directions from Old Scatness will be further refined. This success with Old Scatness suggested that the use of Bayesian modelling to obtain an estimate of the last use of a fired feature was both a feasible and practical option.

#### **4.6.2 Case Study 2: Ferrybridge**

This second case study was selected as it provided an example of utilising chronologically diagnostic material, that was directly related to the heated feature sampled for archaeomagnetism. Ahead of major infrastructure works to upgrade and divert the A1 in West Yorkshire, large-scale archaeological excavations were undertaken at Ferrybridge. An area in excess of 20 hectares was investigated due to its proximity to the Scheduled Ancient Monument site of Ferrybridge henge (Roberts 2005: 1). There was evidence that this area had been important from the late Neolithic, when it was a focus for ritual activity, through to domestic settlements during the Iron Age, ending with Iron Age enclosures and burials. Archaeomagnetic dating was carried out on a fire pit (feature 2044) located in part of an Iron Age settlement (enclosure C)

and a Romano-British corn dryer (context 1632) in the succeeding settlement (enclosure D) (Noel 2002). The procedure for obtaining a date of last use for the corn dryer is outlined below, although details on both of the features at this site that were sampled for archaeomagnetism are in appendix 2.

The Romano-British corn dryer at Ferrybridge was composed of a sub-circular stoke-hole at the northern end, a linear fire-box placed centrally and a large rectangular drying area at the southern end (Roberts 2005: 117ff). Although a substantial quantity of carbonised organic material was recovered from both the stoke-hole and the fire box from the last firing event, no samples were sent for radiocarbon dating. There was evidence that the dryer was regularly cleaned out so the ceramic assemblage recovered from the rake out in the drying room was considered to be contemporary with the last use of this feature. This included Black-burnished ware and South Yorkshire Greyware. From other deposits relating to the abandonment of the dryer, fragments of Dressel 20 amphorae also were recovered. Taken together, this has led to allocation of the date range AD120-160 for the last use of this feature (Roberts pers. comm. 2008). This example serves to illustrate how chronological indicators and the excavating archaeologists' interpretation were combined and applied in the absence of radiocarbon dating.

#### **4.6.3 Case study 3: Vitrified hillforts**

This final case study is different in nature to the previous two. Firstly, because it deals with a class of sites, vitrified hillforts, rather than an individual site and secondly, it serves to illustrate the difficulties that can be encountered when attempting to obtain an assessment of when an archaeological feature last cooled down from elevated temperatures. The thought processes described below were applied to all of the features examined during the course of this research; however, the situation

encountered with the vitrified hillforts was uniquely challenging and it highlights some of the issues with the methodology presented here, so it was worth describing in full.

Hillforts have been the focus of British Iron Age studies since the beginnings of field archaeology, due to their conspicuous presence in the present-day landscape (Ralston 2006: 9). Although the interpretations attributed to these sites have altered during the course of the twentieth century (for example, Cunliffe 1984; Hill 1996), the term is still used as a convenient descriptor and typically applied in the broadest terms (Ralston 2006: 12). Many previously unknown examples of this type of site were identified during survey and excavation, during the first few decades of the twentieth century (Cotton 1954), and it was noted that there were different methods of constructing the key characteristic of hillforts, namely the presence of a circuit (or part) of artificial enclosing works or defences. This observation prompted both the process of classifying these groups and attempting to trace the origin of these methods of construction (Childe 1935: 190-221; Avery 1976; MacKie 1979; Ralston *et al.* 1983). One of the subgroups identified was the timber-laced rampart and examples of these have been found all over Britain (Cotton 1954). At some point in the history of some of these sites, in northern Britain, the timber-laced ramparts were set on fire and the subsequent burning vitrified the rocks within the ramparts.

Over sixty stone built forts in Britain exhibit signs of vitrification (Childe 1935: 195) and seven of these vitrified sites have been sampled for archaeomagnetic dating: Craig Phadrig, Dunnideer, Dun Skeig, Finavon, Knock Farril, Langwell and Tap O' Noth (Aitken & Hawley 1967; Gentles 1989; Harris & Hounslow 2010). It was important for the purposes of this research that the dating evidence associated with these sites was re-evaluated. Firstly, because the magnetic data from these sites are included in the current archaeomagnetic SVC (Zananiri *et al.* 2007) and secondly because a previous review has highlighted discrepancies in the dating of what, on the surface at least,



appear to be a morphologically similar class of sites (Alexander 2002). Due to the apparent similarity between these sites and because in all seven cases, sections of *in situ* vitrified wall material were sampled, they were considered together. When attempting to obtain an estimate of age for archaeological material, it is necessary to understand the relationship between the event being dated by the technique used and the event of archaeological interest (Taylor 1987: 15). Therefore, before the dating evidence is reviewed, the process of vitrification is described to clarify the geophysical/geochemical assumptions that will need to hold, for both the material sampled and the dating technique applied to it.

#### *4.6.3i Vitrification*

There have been several attempts to understand the processes that led to the vitrification of geological material (Youngblood *et al.* 1978; Friend *et al.* 2007) and there has been some debate on whether Iron Age societies had the technological expertise to reach temperatures that would effectively melt stone (Brothwell *et al.* 1974). However, the number of locations across Scotland and Western Europe where vitrified forts have been identified (Ralston 2006: 202-212) suggests that this was the case and a particularly good example recently investigated, via archaeomagnetism, is the late Bronze Age settlement of Misericodia in Portugal (Catanzariti *et al.* 2008b). Initially it was believed that in order to obtain vitrification, a flux such as sand or seaweed was added (Brothwell *et al.* 1974), but no evidence has been found for either the use of a flux or the importation of specially-selected geological materials (Friend *et al.* 2007). This led to the conclusion that temperatures in excess of 1000°C must have been obtained, yet attempts to replicate the process of vitrification on a large scale have met with limited success (McHardy 1906; Childe & Thorneycroft 1937; Ralston 1986). Recent work examining this apparent conundrum has obtained some interesting results (Friend *et al.* 2008), which suggests that temperatures around 850°C would have produced the vitrification effect seen at The Torr, in the Scottish Highlands. Given the evidence for contemporary pyrotechnological practices, it is considered much more

possible that temperatures in this range could have been reached during the first millennium BC on a large scale (Killick 2001: 488 table 39.1; McDonnell 2001: 499 table 40.2). Either way, this research demonstrates that this process of vitrification would have involved temperatures over the Curie point for the two main remanence carrying magnetic minerals, magnetite and haematite (Dearing 1999), so in theory this material could archive a TRM signal (section 3.6) after a single heating event (section 3.4).

An interesting finding from chemical analyses was elevated levels of phosphorus (Youngblood *et al.* 1978; Friend *et al.* 2007). This element would not have originated from the parent geological material and cannot be explained by the vitrification process itself, so it has been concluded that it must have been added. One potential source is bone, and it has been suggested that human remains were displayed on the exterior walls of these structures (Ralston 2006: 134-138). This would lend weight to the hypothesis, favoured by archaeologists, that the walls were burnt as an act of destruction (MacKie 1979; Ralston 2006). However, given that people living in Scotland during the first millennium apparently had a penchant for incorporating human remains into their stone-built structures (Armit & Ginn 2007), it could equally support the case for vitrification as part of the construction process, as put forward by those scientists who have analysed vitrified material (Brothwell *et al.* 1974; Youngblood *et al.* 1978). Recent microprobe analysis on a section of vitrified wall from Misericordia, Portugal, suggests that the vitrification process was a single heating event but the possibility of multiple heating events cannot be ruled out on archaeomagnetic grounds (Catanzariti *et al.* 2008b), as only the final heating event is archived by the material via TRM. Therefore, the possibility that these structures were set on fire on several occasions cannot be dismissed. Whilst this debate regarding when the structure was vitrified is potentially pivotal for archaeological interpretations of these structures, it does have some bearing on attempts to directly date the vitrification process. Archaeomagnetic dating provides a date for when the structure last cooled from around 700°C, so it is necessary to determine whether vitrification marked the

beginning or end of use of these structures, in order to identify which chronometric evidence to utilise and how to apply it in order to get an independent assessment of when the magnetic signal was captured. Ideally, a measure of time initiated by the same process as archaeomagnetism would be applied and, of all the potential dating methods, thermoluminescence (TL) could provide such a measure, although the application of this method has several caveats (Aitken 1989).

#### *4.6.3ii Attempts to date vitrified structures*

Previous studies have attempted to obtain a date for vitrified structures (MacKie 1979; Gentles 1993), although they have tended to raise more questions than they answered (Alexander 2002). In general four methods have been utilised: radiocarbon dating (MacKie 1969), TL dating (Sanderson *et al.* 1988), archaeomagnetic dating (Gentles 1989) and associated artefacts (Childe 1946; MacKie 1979). In all, seven vitrified hillforts have been sampled for archaeomagnetic dating: Craig Phadrig, Dunnideer, Dun Skeig, Finavon, Knock Farril, Langwell and Tap O' Noth. Two of these sites have been sampled by two different research groups (table 4.6), with regards to Finavon (Aitken & Hawley 1967; Gentles 1989). Analysis of the data, utilising statistical procedures developed in palaeomagnetic studies (McFadden & Lowes 1981; McFadden & McElhinny 1990), has revealed no statistical difference between the two measured directions at 95% confidence interval. This finding lends support to the hypothesis that molten rock can record a stable TRM signal and that archaeomagnetism can be used to date these structures. Furthermore, as the precise sampling location of the samples analysed by Aitken's team (Aitken & Hawley 1967) are unknown, this suggests that the heating event recorded by both sets of samples from Finavon was a single event. This follows current thinking on vitrified hillforts preferred by archaeologists. However, the on-going debate appears to centre on whether vitrification was part of construction or an act of destruction. The same is not true of the other site, Dunnideer, sampled by two groups (Gentles 1989; Harris & Hounslow 2010), but due to the large difference in scatter of the obtained directions it is suggested that Gentles (1989) may have

collected material that had slumped. Examination of the magnetic directions from the other vitrified hillforts sampled suggests that it is unlikely that they were all vitrified at the same time, or even within a relatively short period of time, given the differences in their recorded TRM signals. This finding implies that there is no merit in applying the same date range to all vitrified sites. Furthermore, these particular sites are geographically fairly disparate, so there is little reason to suppose that they were necessarily all vitrified within a short time frame, as is often implied by the application of cultural groupings. The difficulties of each dating method that could potentially be applied to vitrified hillforts will be discussed in turn, starting with archaeomagnetic dating.

Site	Dec.	Inc.	$\alpha_{95}$	Archaeomagnetic (Date range 1)	Radiocarbon (Date range 2)	TL (Date range 3)	Archaeomagnetic database (Date range 4)
Langwell	355.3	72.8	1.7	100BC-AD100	500BC-AD100	AD25-385	400BC-AD100
Craig Phadrig	354.5	77.2	4.0	200-100BC	800BC-AD600	340BC- AD85	600-400BC
Dunnideer (a)	347.1	61.2	11.3	-	-	-	400BC-AD100
Dunnideer (b)	1.3	74.1	0.9	605-255BC	390-160BC	-	New data
Dun Skeig	3.4	66.7	4.2	AD100-400	-	-	400-50BC
Finavon (a)	353.2	73.4	2.5	200-100BC	800-200BC	AD510- 770	100-0BC
Finavon (b)	350.4	72.8	2.2	-			500-300BC
Knock Farril	355.6	74.1	3.7	200-0BC	-	1430- 820BC	400-50BC
Tap O' Noth	345.6	71.5	3.3	100-0BC	-	2570- 1750BC	400-50BC

*Table 4.6: Summary of the magnetic data (at site) and chronometric data available for the seven vitrified structures in the current British archaeomagnetic database. Date range 1 is that suggested by archaeomagnetic dating of the vitrified material via the Clark et al (1988) calibration curve (Gentles 1989), except for Dunnideer (b) which was calibrated by Harris & Hounslow (2010) using Pavón-Carrasco et al (2009); Date range 2 is suggested by radiocarbon dating (MacKie 1969; Megaw & Simpson 1979; Cook in press); Date range 3 is that suggested by thermoluminescence dating (Sanderson et al. 1988); Date range 4 is quoted in the current database (Zananiri et al. 2007) as dating these magnetic directions and has been used to construct the previous SVC. Finavon and Dunnideer (a) are Gentles (1989) data, Finavon (b) and Dunnideer (b) are data from Aitken and Hawley (1967) and Harris & Hounslow (2010), respectively.*

#### 4.6.3iii Archaeomagnetic dating

All seven vitrified sites were sampled by Gentles (1989) and he was able to obtain an archaeomagnetic date (via a reference curve) for six of them (Gentles 1993); however, the magnetic signal from Dunnideer was too scattered to obtain an archaeomagnetic date (section 5.2 contains a discussion of directional scatter). However, this site has recently been excavated (Cook in press) and this opportunity was taken to resample this site, which provided more precise directional data (Harris & Hounslow 2010). When Gentles' work was undertaken, the archaeomagnetic reference curve in use did not extend past 1AD, therefore it was necessary to use another record of secular variation in magnetic directions to date these magnetic directions. Gentles (1989) decided to use the British master curve of lake sediment data (Turner & Thompson 1982), which in principle provides a valid alternative. However, there is some debate regarding the legitimacy in using sediment data to provide a date for archaeological fired materials, with some authors arguing against (Nourgaliev *et al.* 2005) and others suggesting that the differences between these two records of past secular change in the geomagnetic field are insignificant (Clark *et al.* 1988: 660ff). Chapter 6 of this thesis attempts to address this issue, but it does cast some doubt on the dates obtained by Gentles (1989), who compared the results from the fired material directly to the magnetic directions from the British master curve. Another potential issue is the possibility of magnetic refraction; this phenomenon is not fully understood but it has been cited as causing a distortion in the recorded magnetic field. It has been observed that magnetic directions from large or enclosed features tend to show more scatter than would be expected (Hartley 1961; Weaver 1962; Tarling *et al.* 1986) and deviations of up to 6° have been noted in the inclination values (Clark *et al.* 1988: 663; section 5.3.8), which does suggest that vitrification of a large feature such as the circuit of a hillfort may not be able to provide a representative record of the ambient geomagnetic field. The more recent work suggests that perhaps Gentles (1989) inadvertently sampled material that had slumped or collapsed, something that may not have been apparent as the site was not being excavated when the samples

were collected. Additionally, the direction from the more recent work was calibrated using a Europe-wide magnetic field model, which was derived from a much larger database of information, so is potentially more precise and it avoids any relocation errors. But calibration with the British SVC (Zananiri *et al.* 2007) does not give significantly different results 625-245BC, as opposed to 605-255BC from the European model (Pavón-Carrasco *et al.* 2009).

#### *4.6.3iv Typology*

The problem with applying the date ranges suggested by the associated artefact assemblage revolves around the difficulties in determining whether the vitrification process marks the construction or destruction of the site. Childe (1935: 222f) suggested that vitrified hill forts in Scotland appeared after 200BC and this was based entirely on the artefacts recovered. This has now been shown to be incorrect (Avery 1976), but the evidence on which to build an alternative chronology does not yet exist. This approach is hampered by the lack of diagnostic ceramic sequences for most of mainland Scotland and issues in dating metalwork (Hunter 1997). Interpretation of this monument type has also been limited by the assumption that vitrification is a suitable criteria for grouping them. Placing these sites in a group together implies that they are all contemporary, which may not be the case and appears to have led to issues accepting and incorporating any other dating evidence recovered archaeologically.

#### *4.6.3v Radiocarbon*

A suite of radiocarbon determinations have been collected from Scottish vitrified hillforts (Megaw & Simpson 1979). Unfortunately, none of these are suitable to address the question of dating the vitrification process and arguably neither are they suitable to date the occupation of the hillfort. Four of the sites with archaeomagnetic data (Langwell, Craig Phadrig, Dunnideer and Finavon) have also been sampled for radiocarbon dating. The issue with these radiocarbon determinations lies with the

choice of material sampled and the contexts from which they were recovered, as they do not follow the recommendations made by Ashmore (1999). From Finavon, none of the contexts are particularly secure and either substantial timbers or unidentified charcoal were sampled. Of these, only the timber can be tentatively associated with the construction of the wall, but it does not directly date it and the other determinations cannot be used to date the vitrification process. However, any structural timbers must pre-date the construction and hence the vitrification, so potentially may form a *terminus post quem* and has been recognised in more recent work (Cook in press), where hazelnut charcoal recovered from keyhole excavations at Dunnideer were recovered and applied in this manner, with the assumption that the hazel was cropped no more than 10 years before the burning event. At Craig Phadrig both peat and wood were sampled and both these materials have issues with relating the event dated by radiocarbon to any event of archaeological interest (Bowman 1990). The two timbers recovered from the wall were sampled, but again these can only provide a *terminus post quem* for the wall construction as the most likely situation is that the tree must have been felled before the wall was constructed. At Langwell it would be difficult to relate any of the radiocarbon determinations directly to either the construction/destruction of the ramparts or to the occupation of the site. Finally, there is currently no evidence to support the implicit assumption that vitrification took place immediately before or after the site was occupied; there may well have been a hiatus between these two events. In light of this possibility radiocarbon dating may not be the best method to obtain an estimated date range for the process of vitrification.

#### 4.6.3vi Thermoluminescence (TL)

Perhaps the technique that holds the most potential for obtaining a date range that can be applied to archaeomagnetic directions is thermoluminescence (TL) dating, as they are both triggered by heating to high temperatures. There are several publications that describe the general principles of dating by TL (for example Aitken 1970; 1985; Grün 2001) and its application to archaeological materials (Roberts 1997).



In brief, TL is one of a family of techniques that are based on the principle that certain common minerals (quartz and feldspar) can act as natural radiation dosimeters, because they accumulate electrons within their crystal lattice over time. These are collectively called trapped-charge dating techniques and also include electron spin resonance (ESR) and optically stimulated luminescence (OSL). With TL, these trapped electrons are released as light when the mineral is heated to over 500°C. The time elapsed since the last heating event is represented by the intensity of the light given off when the minerals are reheated; the longer the time that has elapsed, the more electrons will have become trapped, providing a more intense light signal. In principle this technique is straightforward, but unfortunately a dozen or so additional quantities enter into the calibration of the date, so it is necessary to estimate the combined effect of the associated uncertainties for each component. Not all the sources of inaccuracy are completely quantifiable and it is necessary to account for systematic and random uncertainties. The result is that the standard procedure adopted by most laboratories is to quote an error limit of  $\pm 7\text{-}10\%$  of the age (Aitken 1990: 164). Therefore, although trapped-charge dating techniques are particularly useful in establishing chronologies in the pre-radiocarbon time range, they have not been incorporated into more recent chronologies, due to the size of the associated errors. However, it is possible to incorporate luminescence dates into Bayesian models in OxCal, which tends to reduce the estimated age range if it is bounded by radiocarbon determinations. Generally, luminescence samples are not routinely considered for Iron Age archaeology.

#### *4.6.3vii Comparison of the range of dating evidence applied to vitrified hillforts*

Comparison of the date ranges suggested by the radiocarbon determinations to those suggested by TL, as presented in table 4.6, supports the idea that these sites were set on fire as an act of destruction or “sealing” the monument when it was abandoned. Although these two date ranges do not agree, they do show some overlap, at least for those examples that fall within the Scottish Iron Age (Langwell, Craig Phadrig and Finavon), with the end of the range estimated from radiocarbon dates

overlapping with the beginning of the range estimated by TL. Therefore, given the close association between the mechanisms that record magnetic directions and trigger TL, the estimated date ranges provided by the TL dates could be applied to the magnetic directions at Langwell, Craig Phadrig, Finavon, Knock Farril and Tap O' Noth. Although using TL dates will provide Bronze Age date ranges for the magnetic directions from Knock Farril and Tap O' Noth, the possibility of a Bronze Age date is not improbable. TL only provides a date range for the vitrification process, so perhaps with these examples vitrification was part of the construction process or vitrified hill forts are much more ancient in Britain than has been previously assumed. It may also be speculated that Knock Farril and Tap O' Noth represent early examples, that had a prolonged or repeated use. Other larger hillforts in Scotland, such as Traprain Law, appear to have middle to late Bronze Age origins (Armit pers. comm. 2010) and hillforts in Ireland are also generally understood to be early, dating to the late Bronze Age (Raftery 1994: 59). With regards to Dunnideer, the radiocarbon dating provides a similar date range to Langwell and Craig Phadrig, but for Dun Skeig because this site is unexcavated there is neither an associated artefactual assemblage nor the recovery of any other chronometric dating, making re-assessing the dating evidence for this site particularly challenging. It would appear, therefore, that the date ranges currently ascribed to these magnetic directions are still be based on the now out-dated suggestion by Childe that these sites appeared by 200BC (Childe 1935: 222f).

To summarise, the magnetic directions from the vitrified hill forts, except Dunnideer (b), are included in the current archaeomagnetic reference curve (Zananiri *et al.* 2007), but the date ranges ascribed to them appear to have been based on now outmoded theories on the chronology of these sites. As the aim of this research is to not necessarily reduce the age ranges associated with each of the magnetic directions, but to assign date ranges that more accurately reflect the archaeology, it would be prudent to exclude all of these magnetic directions derived from vitrified hillforts from the dataset, until further research is carried out on these monuments. This

recommendation is due to lack of suitable dating evidence because of the difficulties in identifying when the heating event took place and the possibility of magnetic refraction effects when heating large features (Tarling *et al.* 1986; Clark *et al.* 1988) that are still poorly understood. Therefore, it was concluded that none of the magnetic directions from vitrified hillforts should be included in the dataset used to construct the next British SVC. Dunnideer (b) could be included in future SVCs, but the results from this site were not completed in time for inclusion this time around.

#### **4.7 Results from reassessing the archaeological age estimates**

Although only a short time had passed since the British archaeomagnetic database had last been updated, this survey has yielded positive results. Throughout, the focus was on refining the age estimates associated with each of the magnetic directions currently in the British database. This research has now provided a total of 232 directions that originated from British Iron Age sites. Of these, 117 are new additions to the British database. Furthermore, it has been possible to apply the methodology described here to over 95% of the collated data. For ten magnetic directions from the original data set it has not been possible to revise their age estimates. Regarding the directions at Castle Henllys (N=4), Hants (N=1) and Thanet (N=3) it was difficult to obtain any relevant information within the time limits of this research project, despite repeated attempts. For Hants and Thanet, in particular, it was difficult to even positively identify which archaeological site these directions had been collected from, never mind any considerations regarding the stratigraphic relationships of the features sampled. Regarding Castle Henllys, it is understood that publication is advancing both on the monograph of Castell Henllys itself and for a paper on the collaborative project on enclosed settlements in the region, funded by CADW (Mytum pers. comm. 2010). Therefore, it should be possible to re-evaluate the data from this site in the future. The remaining two directions with unrevised age estimates were from Dorney (N=1) and Springhead (N=1); these sites have recently been re-visited and

are also in the process of being written up. It was believed preferable to leave the data from these five sites unaltered, but to highlight them for future researchers. Consequently, for these 10 directions, the original age estimates currently remain unchanged. Also, thirteen of the new directions currently have no associated age estimate. These have been described as “Pending”, because either excavation or post-excavation work is still on-going. Again, it was decided that it was preferable to leave the age estimates blank at this time, because it would encourage future workers to obtain a reliable date estimate once these sites were completed. The directions affected were from the following sites (with the relevant number of magnetic directions): 89 The Mount (N=1), Blacksole Farm (N=2), Castlemill Airfield (N=3), Grand Arcade (N=2), Rose Hill (N=1), Watlington Quarry (N=3), and Wygate Park (N=1). This means that there are now 218 magnetic directions with an associated independent age estimate derived using this methodology. Section 4.7 will present the results of applying the reassessment process. In order to fully assess the impact of the approach presented here three aspects will be considered: the reliability, the precision and the distribution of the data across the target time period.

#### **4.7.1 Summary statistics and reliability of the dataset**

The logic behind this reassessment procedure was not necessarily to reduce the range of the age estimate associated with each magnetic direction, but to improve the confidence and reliability of the age estimate and ensure that they reflect the nature of the associated archaeology. However, due to the regional differences in archaeology, as discussed in section 2.2, there was reason to be confident that a reduction in age range would result from the critical application of archaeological information. A comparison of the three measures of central tendency, applied to the age estimates for the original and revised dataset shown in table 4.7, highlights the overall reduction in the size of the age ranges associated with each of the magnetic directions that relate to British Iron Age archaeology.

	Original data, n = 115	All data after, n = 232
Average age range	±206	±136
Median age range	±100	±90
Mode age range	±372	±50

*Table 4.7: The average, median and mode age ranges associated with the magnetic directions examined before the re-evaluation, where only 115 directions were available and afterwards, when 232 directions had been collated. The fieldwork detailed in chapter 5 are not included here.*

Moving on to the quality of the magnetic data, the original dataset contained 115 directions and these consisted of typically good-quality magnetic data, but the age estimates were poor, with low resolution and no measure of their reliability. Having doubled the number of entries in the database it was decided to examine the overall quality of the original dataset to determine whether the new magnetic directions were of similar or improved quality. This examination began with the magnetic data and the magnetic ranking system devised by Tarling (1991) was applied to both the original dataset and the total revised data (figure 4.7). In Britain, any magnetic direction with an  $\alpha_{95}$  below  $5^\circ$  is considered suitable for dating purposes (Clark *et al.* 1988). In the original dataset, only 20% met this criterion and now 68% have an  $\alpha_{95}$  under  $5^\circ$ , suggesting that not only has the absolute number of data points increased, but that the dataset now includes more high quality magnetic data. These pie charts also show that a high proportion of data in the original dataset was poor, with a third of the magnetic directions displaying an  $\alpha_{95}$  over  $9^\circ$  which, with the addition of new data has shown a slight reduction, as now 28% of the data have a  $\alpha_{95}$  over  $9^\circ$ . Again these results suggests that the majority of the new data were of a higher quality and this should have a positive impact on any resultant SVC produced from this dataset.

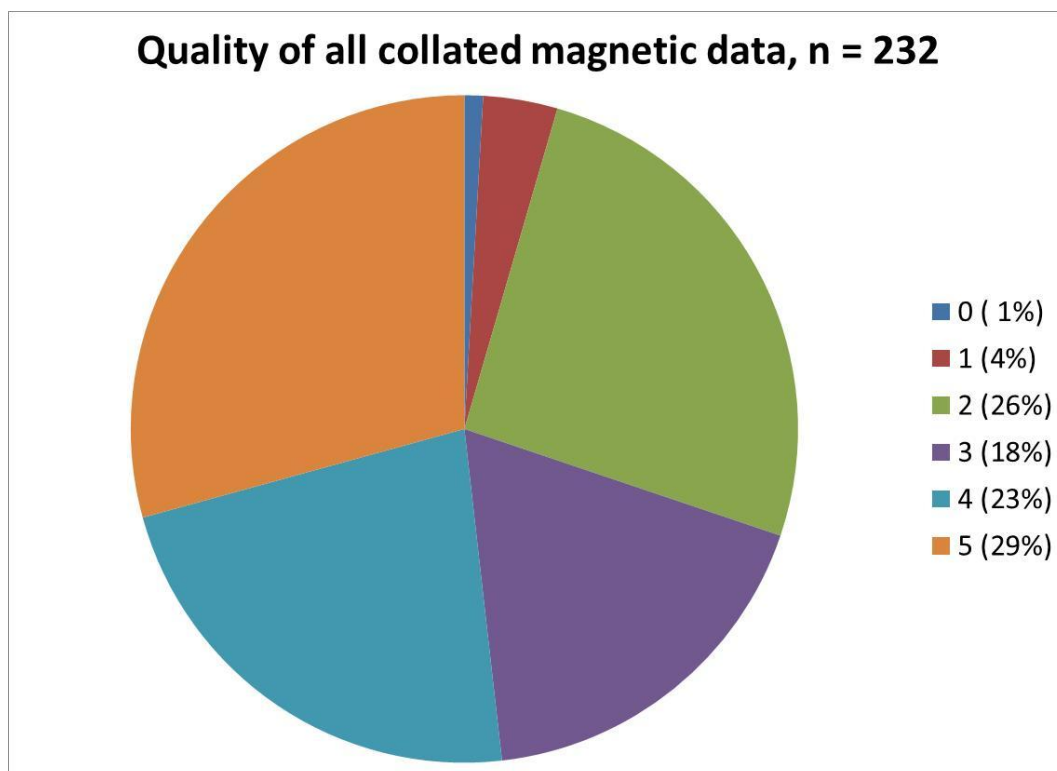
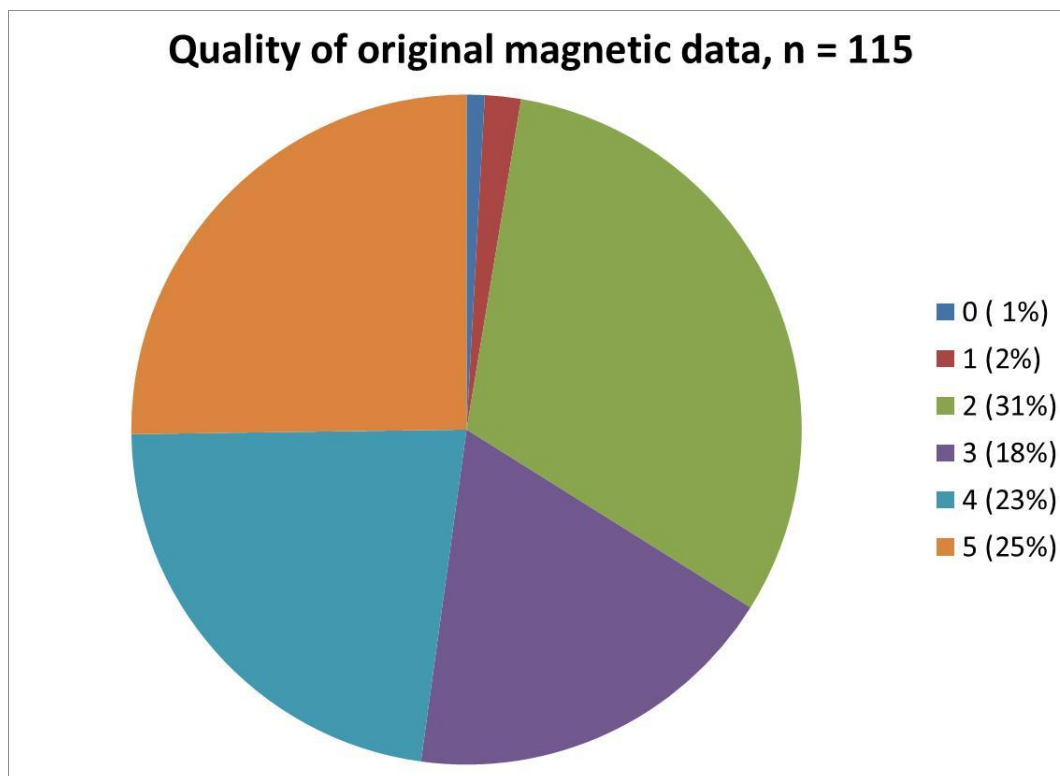


Figure 4.7: Pie charts showing the reliability of the magnetic directions before (top) and after the reassessment (bottom). This reassessment used the criteria set by Tarling (1991), where 0 = NRM only and 5 = “best” as listed in table 4.2

In an attempt to represent the effect of this approach to re-evaluating the associated age estimate on the confidence in the age assignments of the original dataset, the criteria set out in table 4.4 were applied to the original data and figure 4.8 shows that the age estimate for 77% of the original dataset was class C (doubtful) and that none of the age estimates fell into class A (complete confidence). After the re-evaluation process it is clear that class C is still the largest proportion of the dataset, mainly because there was no direct stratigraphic link to the associated dating evidence. This result is probably because many archaeological excavations undertaken over the last twenty years have been developer funded open-area excavations, with little vertical stratigraphy. The other problem alluded to in section 4.4.1 is the nature of the dating programme implemented at most sites. The focus has typically been on obtaining dates for the start and duration of the entire site, whether it is a settlement or industrial area. The choice of dating evidence has been to facilitate a general narrative of the site as a whole, rather than focus on the history of an individual structure or area, although often this situation could be resolved by discussion with the site archaeologist.

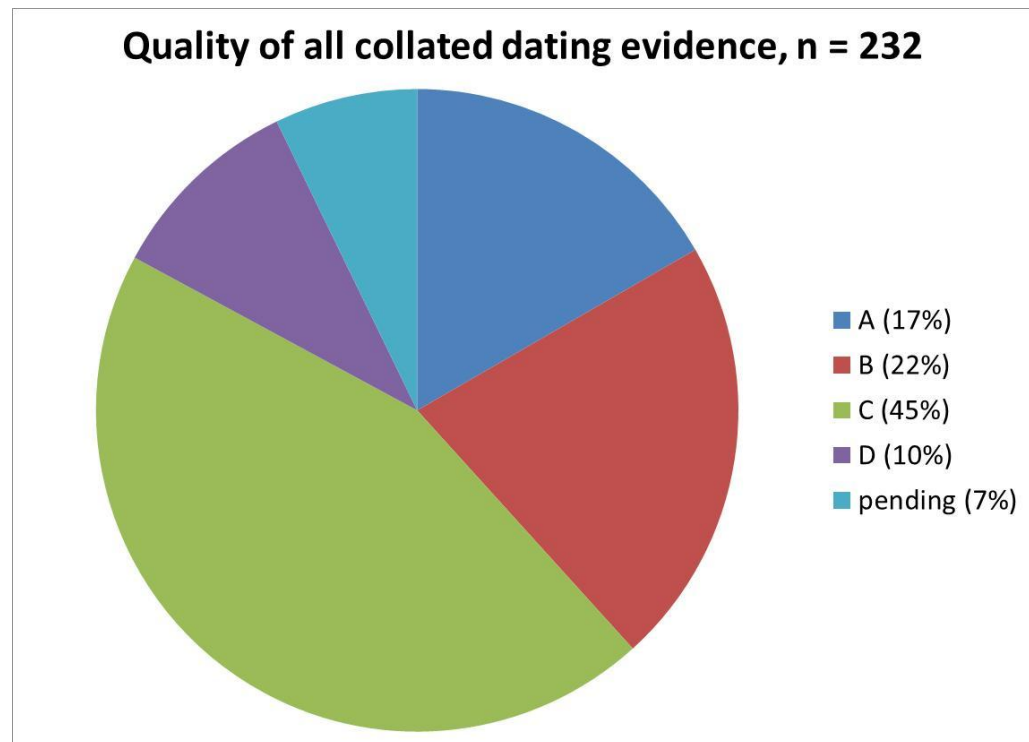
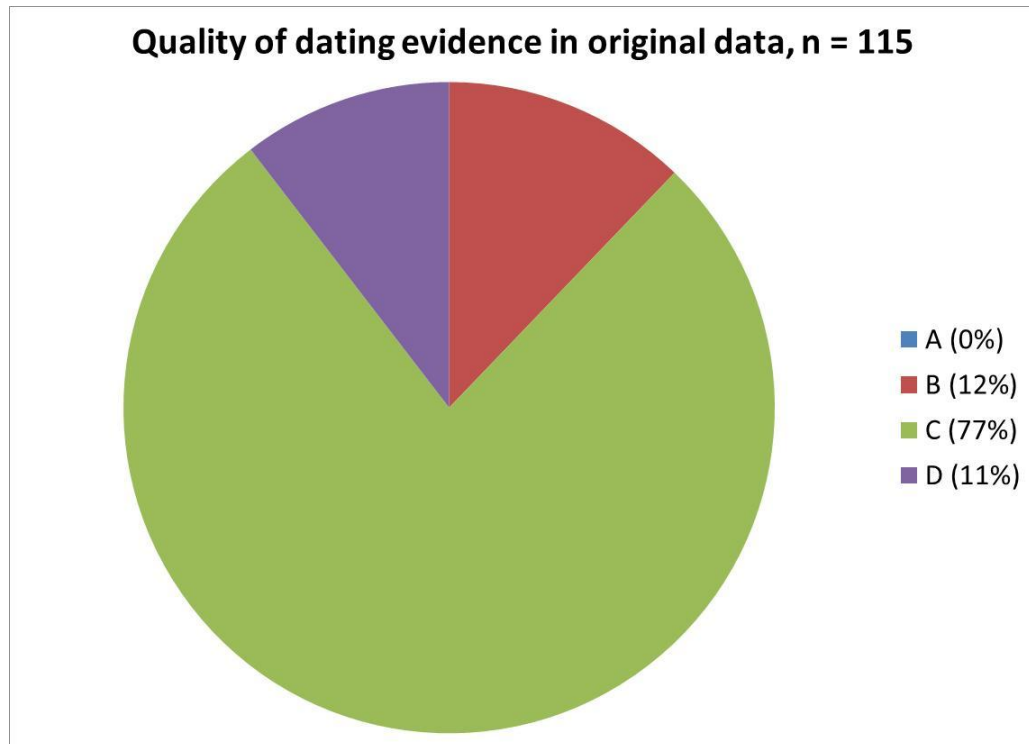
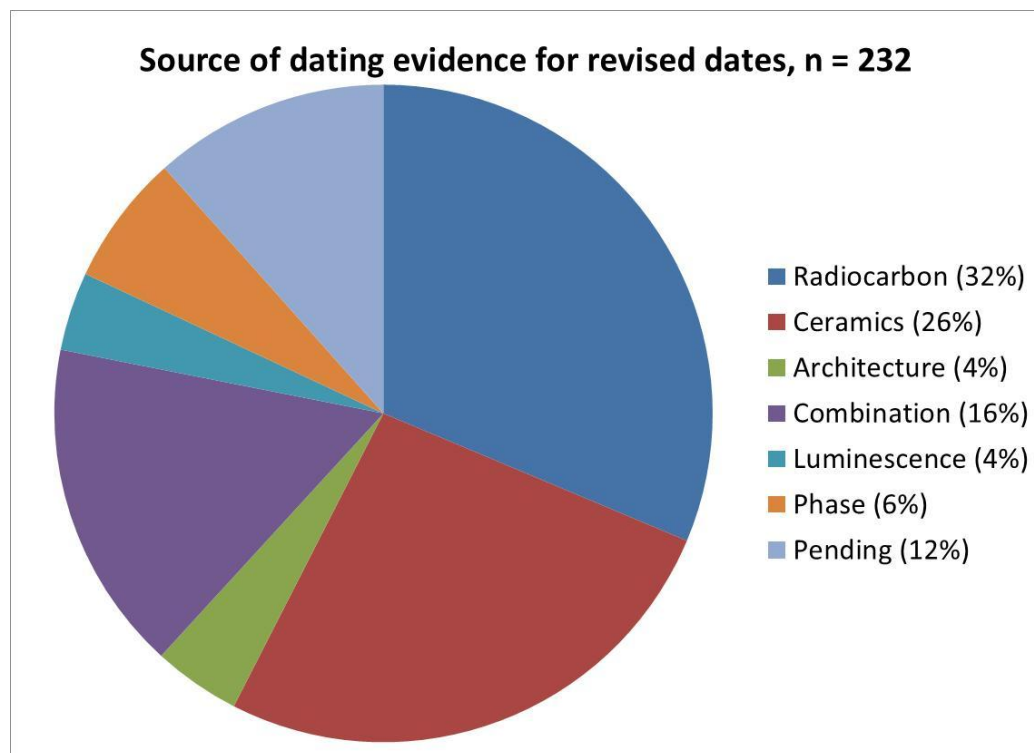


Figure 4.8: Pie charts showing the level of confidence in the age assignment of the dataset before (top) and after the collation and re-evaluation process (bottom): A = complete confidence; B = reasonable confidence; C = doubtful worth considering; D = very doubtful (table 4.4).



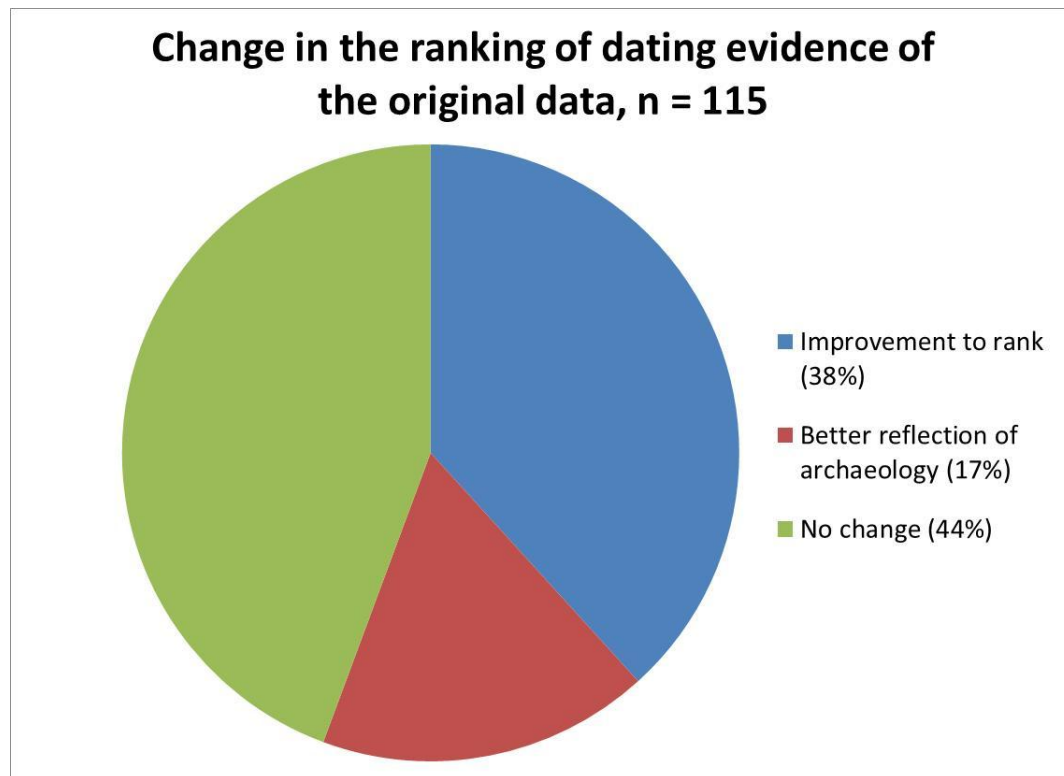
This approach has led to significant improvements in the quality of the age estimates in the dataset, because now over a third of the dataset has an age assessment with a reasonable level of confidence in the reliability of the date. Figure 4.9 shows a breakdown of the source of the dating evidence utilised in the revised dataset and shows that the majority of magnetic directions have now been dated via the application of radiocarbon dating; the next most commonly applied dating techniques are ceramic typology and a combination of evidence. The term “Combination” in this situation is meant to imply that several strands of dating evidence were used together to reach the age estimate. For example, at the site of Crawcwellt, North Wales, radiocarbon dating of the contexts that pre-dated the furnaces suggests that the furnaces could not have been built before 300BC (Crew 1998). The phase with the furnaces was believed to have continued in use to around AD50, on the basis of a glass bangle, as not many chronologically diagnostic artefacts were recovered. The estimated date range associated with the bangle was based on analysis of the chemical composition to around AD1-50, because it was considered to pre-date the Roman occupation of the area by Agricola AD74-78 (Crew 1989). Due to the lack of other associated dating evidence it is only possible to suggest that all of these magnetic directions date to between 300BC-AD50. Now that each of the age assignments has been re-assessed, the next step would be to see if these new more reliable date ranges are more precise.



*Figure 4.9: A pie chart showing the breakdown of the sources of dating used to obtain the independent age estimate associated with each magnetic direction in the revised dataset.*

#### **4.7.2 Impact of the reassessment on the precision of the dataset**

This section will assess the impact of the reassessment process on the range of age estimates associated with each magnetic direction and will begin by examining the difference made by applying the approach adopted in this study to the original dataset. It would appear that even without the addition of new data this research has made a considerable improvement to the overall quality and precision of the original dataset (figure 4.10). The implication of this is that any new SVC constructed with these original data would be more representative of the actual changes in the geomagnetic field during the first millennium BC. Unfortunately, it was not possible to apply more reliable sources of dating to all of the magnetic directions examined, so just over 40% remained unchanged. However, it was possible to assign dates from more reliable sources for just under 40% of the data and only 17% saw the reliability of the dating source decrease.



*Figure 4.10: A pie chart showing the influence of re-assessing the nature of the dating evidence associated with each magnetic direction on the quality of the data employed.*

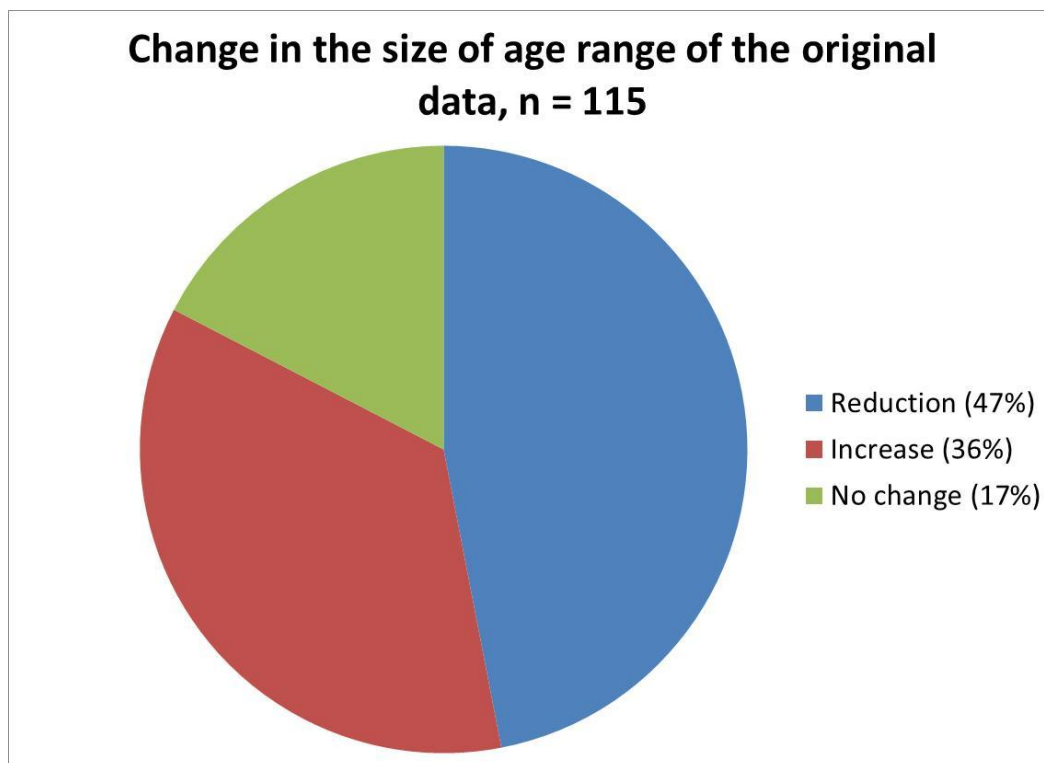
Typically, the decrease in rank was due to over confidence in, or a misinterpretation of, the nature of the dating evidence by previous workers. Many age errors relate to hillforts from southern England and the reduction in the confidence of the age assignment reflects changes in the understanding of this class of monument, since they were excavated in the 1950s and 1960s (section 2.3). One example that shows how the re-evaluation process could lead to no change or a decrease in the reliability of the dating evidence is Hascombe hillfort, Surrey. This site is a univallate hillfort, scarped on three sides, with a carefully planned stone revetted entrance to the north-east. It encloses an area of 2.5 hectares and was initially excavated in 1931. Although the number of finds recovered was not large, a number of ceramics were recovered (Thomas 2010). A second series of excavations were undertaken from 1975-1977, which included a complete gradiometer resistivity survey of the earthworks (Thompson 1979). These excavations tended to focus on the anomalies highlighted by

the geophysics and the entrance (Thompson 1979: 269-294) and two of the 12 anomalies identified were sampled for archaeomagnetism. On excavation one turned out to be a burnt kidney-shaped pit (77/2) which was sampled for archaeomagnetic dating. This pit contained ceramics dated to 150-50BC and an adjacent pit (77/6) contained a similar ceramic assemblage, but also yielded 3 class I potin coins dated to 60-50BC, which provides a *terminus post quem* for the second pit. It has been assumed that the occupation at this site was short, so these two pits were considered contemporary (Clark & Thompson 1989). The assessment of the reliability of this age estimate had previously been stated as class B - reasonable confidence - and this reassessment did not alter this interpretation.

The second archaeomagnetic direction for this site (77/7), was collected from the exterior V-shaped ditch that defined the interior of the site. The only artefact recovered from this area was a “characteristic bead rim Wealden vessel” (Thompson 1979: 272). In this region’s typological sequence this style is understood to date to around 100BC-AD43 and the author believed that Hascombe was abandoned between 200-50BC (Thompson 1979: 300). As the archaeological interpretation of Pit 77/2 was that it was quickly filled as the site was abandoned (Thompson 1979: 279), it was reasonable to compare the magnetic direction from the pit to the silting of the ditch represented by 77/7, because given this interpretation of the site they should be broadly contemporary. Comparison of the magnetic directions obtained from these three ditches, utilising the statistical procedure developed in palaeomagnetic studies (McFadden & Lowes 1981; McFadden & McElhinny 1990), revealed that although these magnetic directions had different precisions there is no significant difference between them at 95% confidence level. In the absence of any contradictory information, it would appear sensible to apply the same date range to both directions. This assessment of the reliability of this age estimate had also be stated as class B; however, there are several assumptions behind giving these two directions the same age

estimate and there is no direct link between them, so this age estimate was demoted to class D – very doubtful.

Turning now to the associated age ranges, this reassessment has enabled nearly half of the associated age estimates for the original data set to be reduced (figure 4.11). For a substantial number of directions (17%) it was not possible to improve on previous estimates of age, which leaves around a third of the dataset with larger age estimates after the re-evaluation process. Looking at this in more detail reveals that many of the directions which show an increase in the estimated age range, actually started with unrealistic age ranges. The largest increase was 660 years but this was for a direction from Wallington that previously had no estimate of error. Other sites had age estimates with improbable levels of precision; the most extreme example is Pit 77/2 from Hascombe (see above) which previously had an age estimate of 55BC  $\pm 5$  years. More typically, errors in the range of  $\pm 15$  years were quoted and for most sites these were also found to be unduly optimistic. At the other end of the scale, the largest decrease in age range was by  $\pm 1035$  years, for the site of Trewlowthas, where the application of radiocarbon dating enabled a more precise age estimate to be allocated (Nowakowski forthcoming); full details are in appendix 2. Looking at the overall changes in the estimated age ranges associated with the dataset revealed that, on average, there has been a decrease of  $\pm 70$  years to the age ranges. Perhaps predictably, the most common change has been  $\pm 300$  years as many of the generic “Iron Age” assignments have been replaced with age estimates that reflect the archaeology associated with the feature sampled for archaeomagnetism.



*Figure 4.11: A pie chart showing the impact of the reassessment process on the precision of the age estimate associated with each magnetic direction.*

With regards to constructing a SVC that is to be used for calibration purposes, it is generally considered preferable to use magnetic directions with total age ranges of 200 years or less (Aitken 1960) and figure 4.12 shows the dramatic difference between the size of the age estimates before and after this reassessment. In addition, a good proportion of the dataset now meet Aitken's (1960) age criterion. One aspect that may at first appear slightly misleading is the apparent drop in the number of directions in the 0-50 year error category. In the original dataset, 44 directions fell into this category; however, the directions from Wallington, West Stow, Piercebridge and Keay's Lane were only included as they had no error estimate associated with them and it was highly unlikely that it would be possible to provide an age range that was specific to a single calendar year, even for a Roman site. The re-evaluation process revealed that these original estimates were indeed incorrect. The age estimates for the remaining directions originally in the 0-50 category were mostly rank C – "doubtful but worth

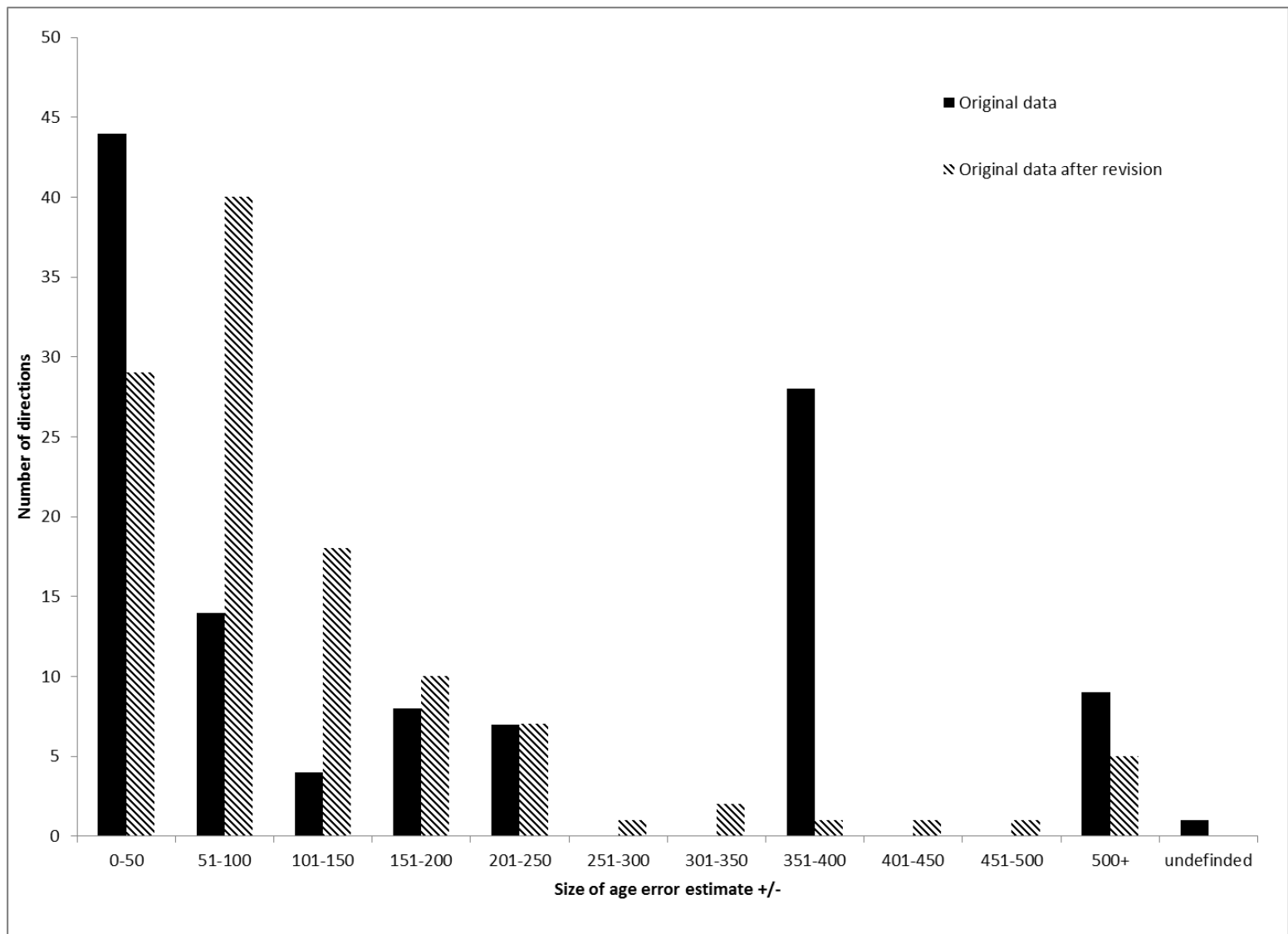


Figure 4.12: Bar chart showing the size of age error estimates divided into 50-year bins for the original dataset,  $n=115$ : before (black) and after (stripes) the reassessment process. The “undefined” category represents those data with no age error estimate.

considering” or D – “very doubtful”, meaning that the apparent precision was misleading. The re-evaluation process caused a drop in the number of data values in this first category, but the majority of data in this category are now rank B – “reasonable confidence”. Another aspect to figure 4.12, that is worth highlighting, is the obvious peak in values for the original dataset relating to the 351-400 year category; all these data had just been assigned “Iron Age” so their associated age estimate was  $329\text{BC} \pm 372$ . There is now only one site in this category, Easington, which is Bronze Age. Given Aitken’s (1960) age criterion it is worth describing those directions that have age ranges greater than 200 years, to illustrate that this is the best that can be currently obtained with the available evidence. So, moving left to right from the 201-250 year category, the directions in each category are from the following sites, respectively: Moel y Gerddi, Wallington, Easington, Old Scatness, Hants, Thanet and the new site of Cladh Hallan. All of these age estimates are rank C – “doubtful but worth considering” or D- “very doubtful”, because the available dating evidence could not be directly related to the last heating event of the feature sampled. Regardless, this is still a large improvement on the previous situation and these new estimates provide a truer reflection of current archaeological understanding. However, by exploiting stratigraphic relationships, the directions with larger age ranges from two of these sites, Old Scatness and Cladh Hallan, will be reduced during the construction of future SVCs (section 7.4.2).

Most of the age estimates that are larger than  $\pm 250$  years relate to magnetic directions from Bronze Age sites, with one exception, the site at Wallington, which had originally been assigned an Iron Age date of 200BC but is actually a Saxon site (Orton 1980). The only new data to have an error estimate greater than  $\pm 250$  years are from the Bronze Age site of Cladh Hallan; full details are provided in appendix 2 but the salient points are highlighted here. At this prehistoric settlement site, on the island of South Uist, excavation revealed a series of sunken floor buildings dug into the calcareous sand, up to 1 metre below ground level (Marshall *et al.* 1998; Parker



Pearson *et al.* 2001). Collectively they contained evidence for around a millennium of continuous occupation, with eight separate hearth features sampled. The ceramic assemblage suggests occupation was during the Later Bronze Age to early Iron Age transition (Marshall *et al.* 1998). Although there was some evidence for metalworking and pottery manufacture recovered from these structures, unfortunately most of the finds were not chronologically diagnostic. The program of radiocarbon dating employed at this site appears to focus on dating the human remains deposited within the houses, rather than the occupation of the houses themselves (Parker Pearson *et al.* 2005), so had a limited application to this research. However, optically stimulated luminescence (OSL-601) samples were collected from the base of a sand core of the shared walls of houses 1370, 401 and 801 (Gilbertson *et al.* 1999: 447 figure 5), so the first phases of activity within each house would have occurred sometime between 2505-545BC. This difficulty has given rise to the large age estimates that have been associated with the magnetic direction from this site.

There is a possibility to reduce the large age estimates at Cladh Hallan, using the unique stratigraphic relationships at this site. Seven consecutive hearths are present within a single structure, because the three “houses” excavated could be considered as a single unit. Therefore, if it could be coupled with the dating evidence from Cladh Hallan, which suggests all of the hearths would have last been used between the period 1200-200BC (Parker Pearson *et al.* 2009), it should be possible to calculate smaller age estimates for each of the hearths within that 1000-year period. Therefore, this site would lend itself to Bayesian analysis similar to that carried out at Lübeck, Germany (Lanos 2004; Schnepf *et al.* 2009), which employed hierarchical modelling constrained by the stratigraphic relationships of the sampled features. These stratigraphic details were included so that they could be utilised in future SVCs (section 7.4.2), so the actual age estimates for Cladh Hallan used to produce a future British SVC will be much smaller than  $\pm 400$  years. Finally, figure 4.13 shows how new and original (Zananiri *et al.* 2007) data are distributed within each age error size category, after the revision

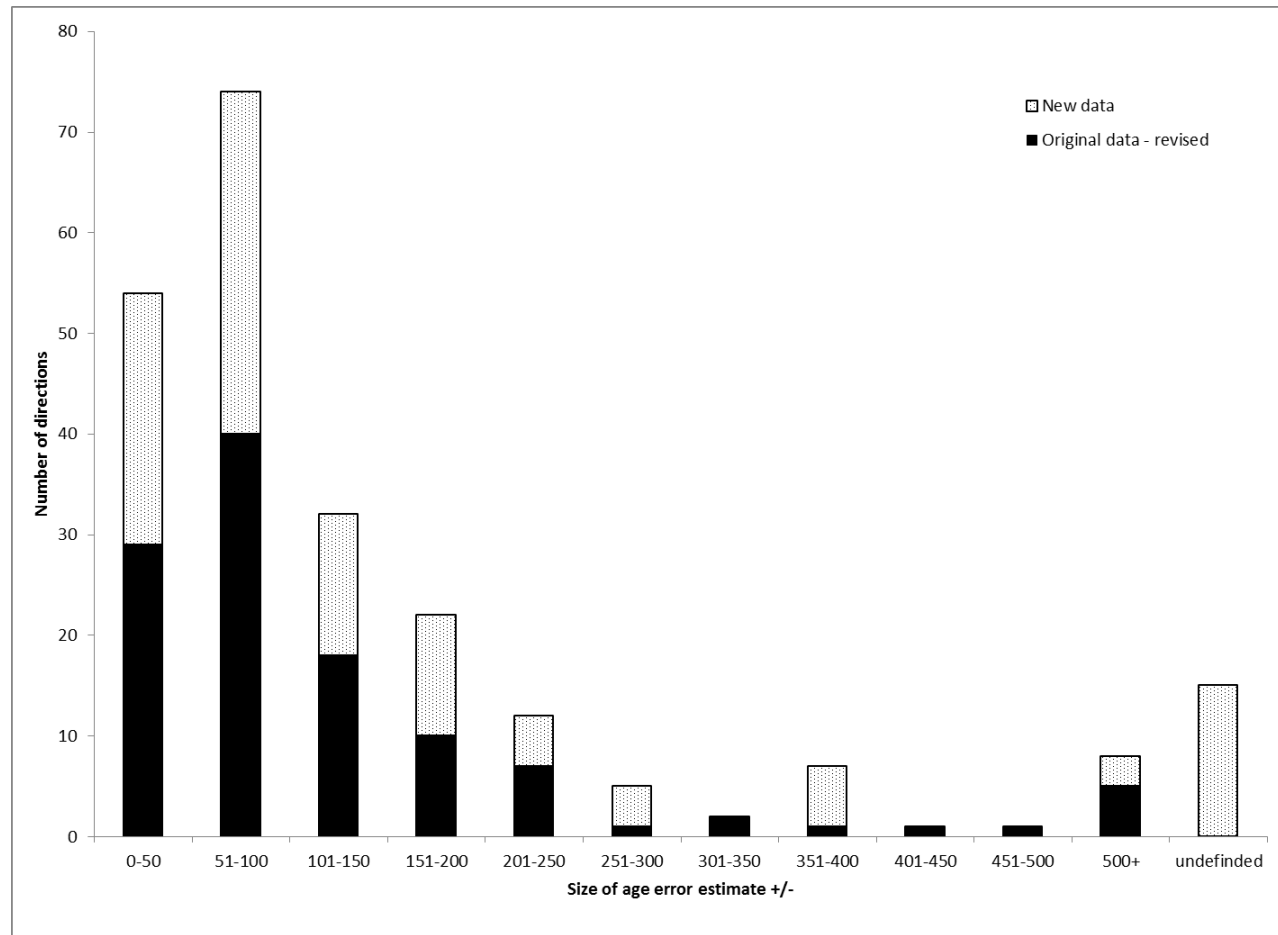


Figure 4.13: Bar chart showing the size of the age error estimates divided into 50 year bins for the dataset after revision, which contains both the original (Zananiri et al 2007) data (black,  $n = 115$ ) and the new collated data (dots,  $n = 117$ ). The “undefined” category represents those data with no age estimate, i.e. excavation is still on-going. Note that most of the data now falls to the left-hand side of the graph meaning that many now meet the age criteria set by Aitken (1990: 243); those still with age errors over  $\pm 250$  years are typically Bronze Age sites.

process. This demonstrates that revisiting older excavations is worthwhile and that more recent excavations do not necessarily provide smaller age estimates.

#### **4.7.3 Effect on the chronological distribution of the dataset**

The final aspect to be considered is how the reassessment process has affected the chronological distribution of magnetic directions over the first millennium BC. In the original dataset there was a single site that had an entry containing details of the magnetic direction, but no associated age estimate, this being Wallington, London. It has now been possible to both identify the site and provide an estimate of age for this magnetic direction. In the revised dataset, thirteen magnetic directions have no age estimate and this is because the sites were either still being excavated, or in post excavation, when this stage of the research was being completed. It was decided that the magnetic data should be included in the database at this time and future workers could follow up on the age assessment; details of the persons and institutions involved in these sites can be found in appendix 2. The relevant sites (with associated number of magnetic directions) are: 89 The Mount (N=1), Blacksole Farm (N=2), Castlemill Airfield (N=3), Grand Arcade (N=2), Rose Hill (N=1), Watlington Quarry (N=3), and Wygate Park (N=1), details are in appendix 2. In some respects the effect of this re-evaluation process on the temporal distribution of data points is perhaps the most important aspect, considering that these data are to be used to create a regional archaeomagnetic SVC for Britain. In order for any calibration curve to be reliable it is considered necessary to have at least five, but preferably ten, well-dated magnetic directions per century (Bucur 1994) and this section will discuss whether or not this target has been reached.

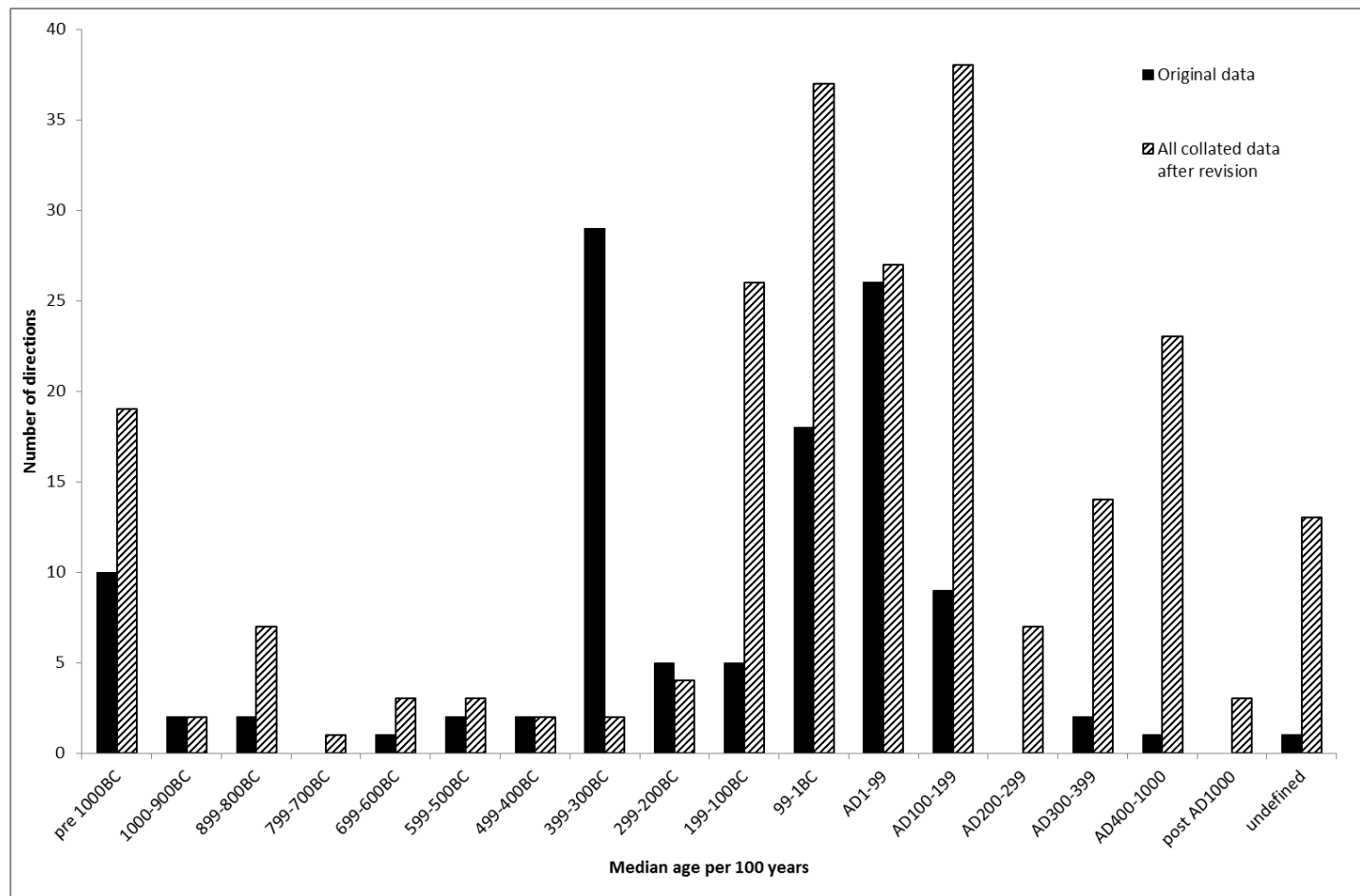


Figure 4.14: Bar chart showing the distribution of data points per century of the original dataset,  $n = 115$  (black), and the entire revised dataset,  $n = 232$  (stripes). The “undefined” category represents those data with no associated age estimate. Note the change in dispersal of data between original and revised, reflecting the contribution of magnetic directions from Scottish Iron Age sites with their longer chronology.

The effect of the re-evaluation on the distribution of the data points through time is shown in figure 4.14. The most obvious aspect is that much of the data are more recent than was previously stated. This is a direct result of recognising the different “Iron Ages” that are represented in British archaeology. The majority of the magnetic directions from Old Scatness, Shetland, are Iron Age but in the long chronology of Scotland (Foster 1989) so many now fall within the first millennium AD. As stated above (section 4.2), the decision was taken to include early Roman sites up to AD100. The re-evaluation process has highlighted that several of these sites were misrepresented as late Iron Age/early Roman, when in fact they showed some continuity of use. So, although established in the Iron Age, some sites were in use until around AD300 and as archaeomagnetism dates the last heating event of a feature, the age estimate associated with the magnetic direction should reflect the end of use, for example Bryn y Castell, in north-west Wales (Crew 1986). Other examples, where the feature sampled for archaeomagnetism are now more Roman than Iron Age include Keay’s Lane, Cumbria (McCarthy 2000), Piercebridge, Durham (Grew 1981) and the magnetic directions from Garden Hill, Sussex (Money 1977), that had previously been designated as Iron Age. All of these new age estimates now reflect better the actual relationship between the events that archived the ambient geomagnetic field and the point in time this event can be identified from the archaeological record.

Other sites that now cover the first millennium AD include the data in the period AD300-399, which are from Bestwall Quarry, Dorset (Ladle forthcoming). This is a multiperiod site showing considerable continuity of use, but the kilns sampled for archaeomagnetism were mostly likely to have been in use until the late Roman period. The magnetic directions for the rest of the first millennium can be broken down as follows. The period AD400-600 includes more magnetic directions from Bestwall Quarry and some from Roman bath houses at Whitehall Farm, Northamptonshire. These magnetic directions will most likely have been recorded during the final use and abandonment of this high status Roman site (Young 2005 and pers. comm. 2009). The

remaining magnetic directions cover the period AD600-800 and are all from Old Scatness, Shetland, and relate to the end of occupation in the Pictish period, a late Iron Age cultural group relevant to Atlantic Scotland (Dockrill *et al.* 2010). Finally, the directions in the post AD1000 category are from the site of Dan-y-Coed, Pembrokeshire. These were originally designated as early Roman, but re-evaluation has uncovered that these directions are most likely from medieval activity at this site, due to evidence from radiocarbon dating of associated deposits (Blockley 1998).

A further consequence of this research is that the data set now contains more data points from Bronze Age sites. Originally, eight sites were stated as providing magnetic directions that related to the Bronze Age: Ascott-under-Wychwood, Dorney, Easington, Gwithian, Hants, Thanet (N=3), Trelystan, and Potterne (see appendix 2 for references). With the exception of Hants and Thanet (as it has not been possible to revise the data from these sites, see section 4.7) the reassessment has confirmed and refined the Bronze Age date range assigned to the magnetic directions, using the results from the most recent dating programmes (Needham 1996; Needham *et al.* 1997). Four new Bronze Age sites have been added: Brean Down (Bell 1990), Cladh Hallan (6 directions that are Bronze Age), Kingsdale (Batty & Batty 2007) and Moel y Gerddi (Kelly 1988). Interestingly, five sites that had originally been classified as Iron Age due to the re-evaluation process now have Bronze Age designations (figure 4.14). These are Knock Farril, Little Bay, Mucking, Sharpstones Hill, and Tap O' Noth, due to focusing on where the heated features belonged in the overall site chronology (details are in appendix 2). This process would have been difficult to undertake during excavation and was only possible now that these sites have been written up. The magnetic direction from Sharpstones Hill was one of three directions that a previous review of the quality of the available archaeomagnetic data in western Europe had rejected, because they were considered to be discordant with other data (Gallet *et al.* 2002). The other two were from Moel y Gerddi (previously called Harlech) and Garden Hill. Following re-assessment, Moel y Gerddi has now been assigned a larger date range

(was  $435\text{BC} \pm 15$  is now  $468\text{BC} \pm 260$ ) and GAR-490 from Garden Hill an earlier date range (was  $50\text{BC} \pm 50$  is now  $\text{AD}145 \pm 75$ ), strongly suggesting that the problem with these data lay predominately with the assigned date range.

Overall, the median age range of the original data is now 50 years earlier than previously stated. The average shift in median date (either earlier or later) is around 300 years, which is misleading because it suggests that most of the previous work was wildly incorrect. Actually, in most instances, it was found that smaller adjustments were made by considering the site chronology and understanding how the event dated by archaeomagnetism fits in with the overall site narrative. The most common shift in date to an earlier one is 125 years, whereas the most common shift to a later date is 200 years, and these are much more representative of the actual changes made. Unfortunately, these refinements have still left the period 800-300BC poorly represented (figure 4.15). It is argued that this gap is perhaps a true reflection of the nature of the British archaeological record during the first millennium BC. It is a subtle point but many Iron Age sites show continuity of use from the late Bronze Age to the late Iron Age or early Roman period (Sørensen & Thomas 1989). Therefore, if archaeomagnetism provides a date for the last use of feature, the early Iron Age will be poorly represented. This situation has been further compounded by the problem that it can be difficult to identify late Bronze Age/early Iron Age transition sites, as well as the under exploitation of archaeomagnetism for prehistoric sites. The fieldwork carried out as part of this research has started to address this problem; for example, the site at Kidlandlee, Northumberland (section 5.3.4). However, that there are still gaps, particularly in the early Iron Age period, which is a problem for archaeomagnetism and archaeomagnetic SVCs. Therefore, it is necessary to find another way to fill in these gaps, which is where sedimentary archives may be useful because they provide a continuous record of secular change in the Earth's magnetic field. This topic forms the focus of chapter 6, where the possibility of using lake sediment data to "fill in the gaps" will be explored.

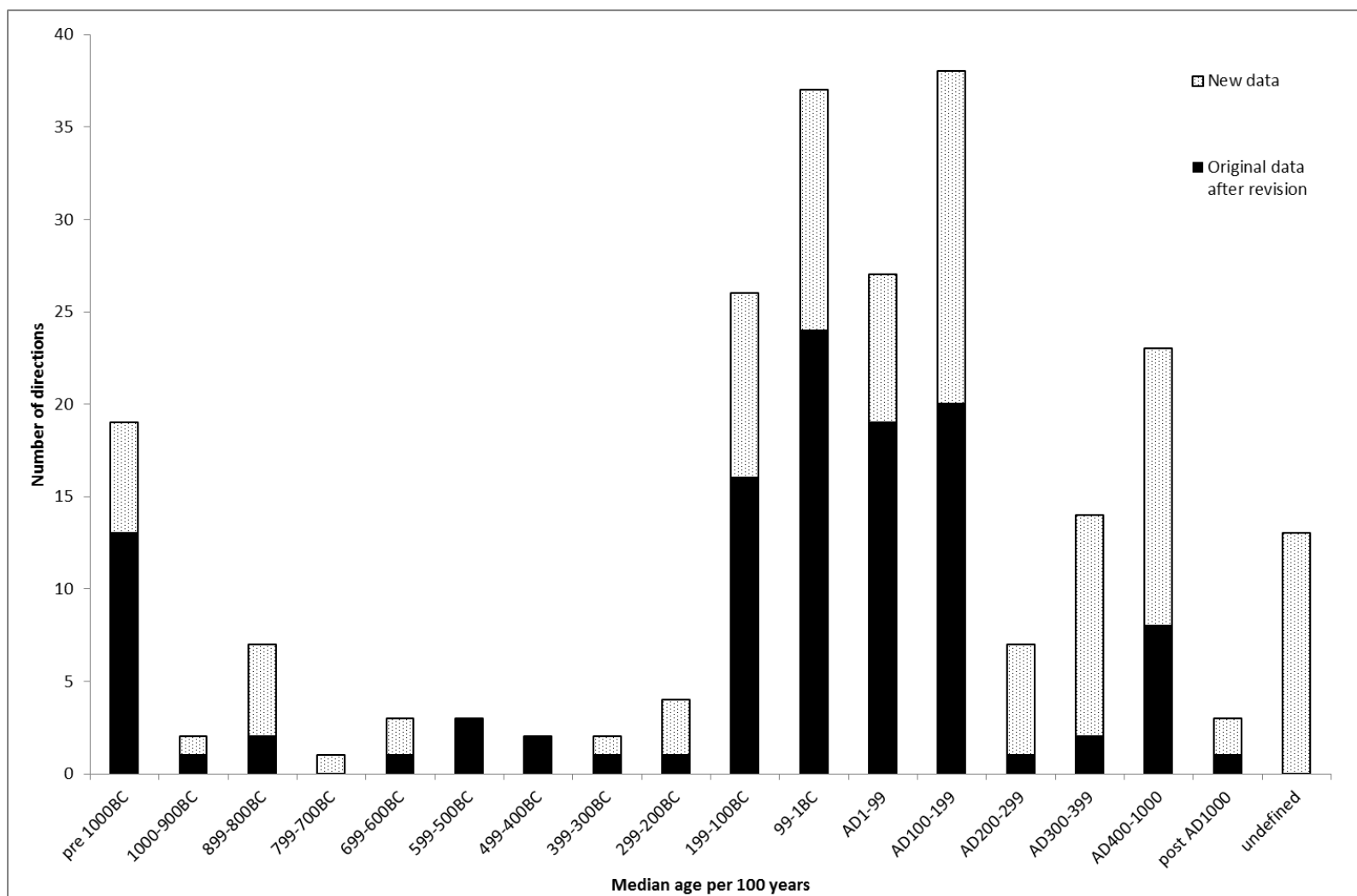


Figure 4.15: Bar chart showing a breakdown of the distribution of data points per century of the revised dataset ( $n = 232$ ) into the original data (black,  $n = 115$ ) and the new data (dots,  $n = 117$ ). The “undefined” category represents those data with no associated age estimate. Note the change in dispersal of data between original and revised, which reflects the contribution of magnetic directions from Scottish Iron Age sites with their longer chronology.



## 4.8 Summary

To conclude, this approach to revising the British SVC by re-assessing the data used to construct it has been successful and the dataset now displays a marked improvement both in quantity and quality. After the review many of the data points have more recent age estimates, due to the regional differences in Iron Age archaeology across Britain that had previously been overlooked. Furthermore, a greater percentage of the data now fit some basic criteria that have been proposed for constructing reliable models, including having at least 5 well-dated points per century, with the error ranges for the magnetic directions under 15°, preferably less than 5°, and the error ranges for the dates being  $\pm 200$  years. As the current British archaeomagnetic dataset is published, it has been used in all of the most recent modelling attempts (Donadini *et al.* 2009; Korte *et al.* 2009; Lodge & Holme 2009; Pavón-Carrasco *et al.* 2009), but for the first millennium BC the original dataset did not fit the criteria relating to points per century or date error ranges. Some workers have made some concessions on the quality of the magnetic data by weighting the analysis towards the more reliable magnetic data (for example, Donadini *et al.* 2009), but no such treatment had been allowed for the archaeological age estimates. The main problem appears to be the level of precision expected, because for palaeomagnetic studies, focusing on geological timescales,  $\pm 300$  years is considered to be a reasonable error margin. In addition, some of the more subtle aspects of archaeological typology dating had been missed. The quality of the dataset is a fundamental aspect of constructing models, particularly if that model is to be used to calibrate future magnetic directions and produce calendar dates, making it important that any data used to create a model of the past secular variation in the geomagnetic field are reliable in order to be able to make meaningful statements about the patterns that are produced.

This review has increased the number of data points recovered from Iron Age sites from 115 to 232. Of these, thirteen magnetic directions were collected from sites that are still being excavated, or are in post-excavation, so currently have

no age estimate. These have been included in the British archaeomagnetic database (<http://www.brad.ac.uk/archaeomagnetism/> and appendix 4) so that they may be updated as the information becomes available. As discussed in section 4.6.3, eight directions relate to vitrified hillforts, which have proven difficult to provide a reasonable estimate of date for so, although they are in the British archaeomagnetic database, it is recommended that they are excluded from the dataset used to create the next British SVC until the issues identified are resolved.

This chapter has provided details on the sources of the data used to construct the British SVC and presented the methods used to assess the quality and reliability of each data point (also see appendices 1 and 2). It has also covered how the dataset was compiled, how the methodology for re-assessing the chronological assignment for each of the archaeomagnetic directions from archaeological material was developed and included a series of case studies which demonstrate the application of this methodology. The difficulties involved with attempting to obtain an estimate of when a specific event occurred, in this case the last time a heated feature cooled down below the Curie point, have also been highlighted. The results from applying this methodology demonstrate that it has had a significant impact. The age distribution of these 210 data points now more accurately reflect the nature of the archaeological record and many original data points now have more precise age; it has also been possible to provide age estimates of  $\pm 200$  years or less for all the new data points. Details on the procedures employed to explore the possibility in incorporating data from lake sediment records are dealt with separately in chapter 6, where both the theoretical and methodological approach is outlined and the results are presented. The next chapter will describe the fieldwork that was undertaken as part of this study to collect new archaeomagnetic data for the British Iron Age.

## 5. Programme of archaeomagnetic dating field work

"I like it, and I went and helped them, I love Time Team! and they had a "celebie come dig a ditchie" type thing and I came and dug a ditchie. And I really dug a ditch! I hadn't dug a ditch all my life! I've never dug a ditch. I never did much ditch digging, you know? I did sand castles and then I did that and I dug. Nothing in it. And that's true archaeology. Sometimes there's nothing in there."

Eddie Izzard "Sexie" tour 2003

### 5.1 Introduction

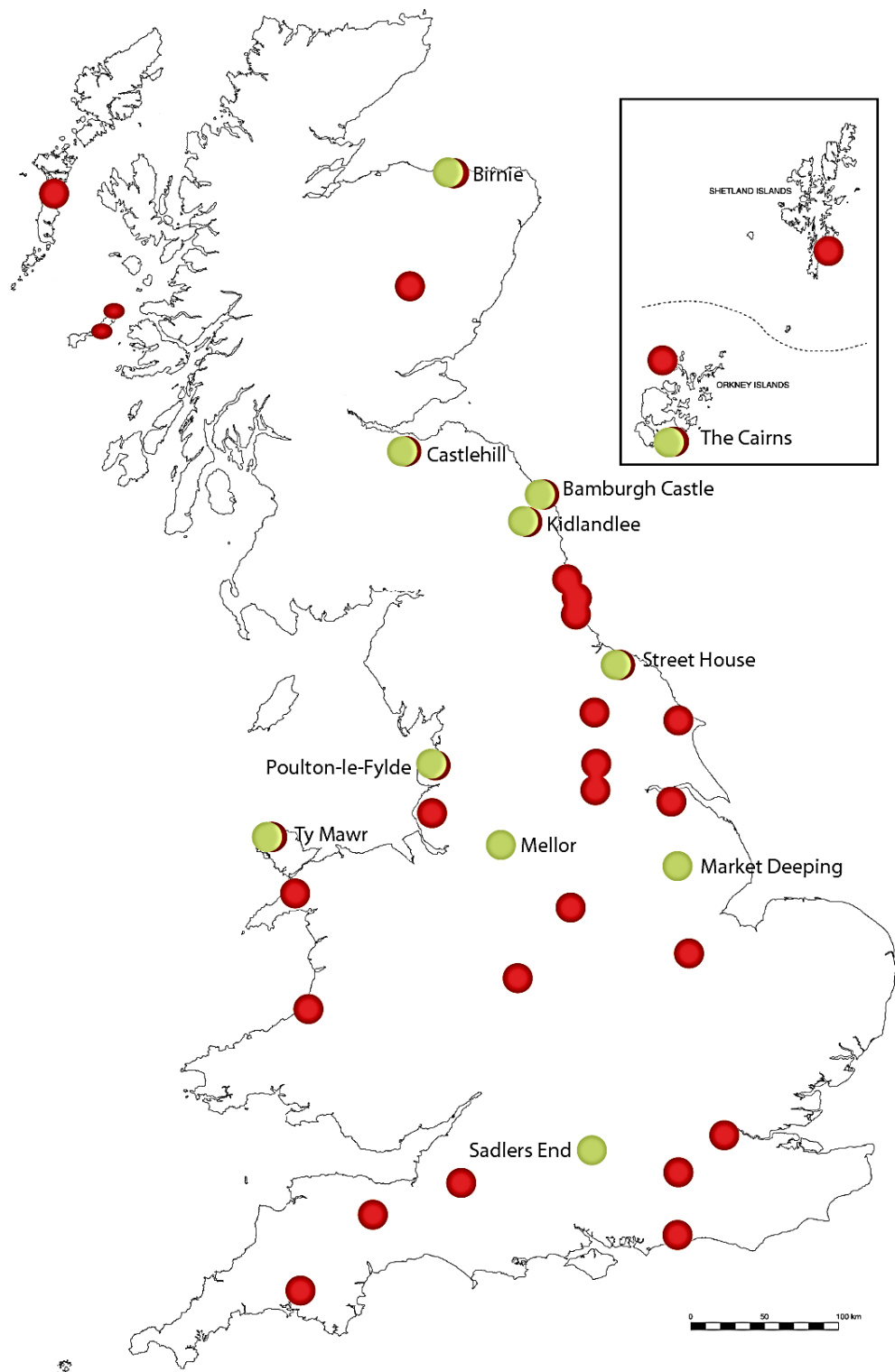
A key component to this research was the collection of new magnetic directions to incorporate into the British secular variation curve (SVC; see objectives in section 1.2). Previous workers who have examined the British SVC have unanimously stated that the first millennium BC is a period that would benefit most from more good quality magnetic data (Hammo-Yassi 1983: 201; Clark *et al.* 1988; Gentles 1989: 288; Batt 1997: 275; Zananiri *et al.* 2007). Therefore, although the collection of new, good quality data is imperative for any revision of the British SVC, it is of particular relevance for this research project. This chapter will provide an overview of the sites sampled during this research and describe the laboratory methods employed to obtain the new magnetic data.

#### 5.1.1 Sites visited

In order to achieve objective 3 (section 1.2), letters of introduction were sent out to 142 archaeological units, the 6 other archaeomagnetic laboratories in the UK, 20 academics whose specialisms included British Iron Age archaeology and the county archaeologist from 93 council districts. Recipients were asked if they were, or would be, working on any potential Iron Age sites over the next 24 months and to get in touch if any features that were suitable for analysis via archaeomagnetism were revealed. Additionally, Historic Scotland, Cadw (the name of the historic environment service for the Welsh Assembly Government) and English Heritage were contacted to request information regarding any planned excavations on Iron Age sites, along with the committee members from local archaeological groups across the UK and, to ensure comprehensive coverage,

adverts were placed in two fieldwork journals: *British Archaeology* and *Discovery and Excavation in Scotland*. Finally, to further facilitate this outreach process, a webpage was published in December 2007 which detailed the research project and outlined the types of features that would be suitable for inclusion in this study <http://www.brad.ac.uk/archenvi/research/postgraduate/Clelland/phd.php>. This thorough approach yielded positive results and by February 2008 details of 34 potential excavation projects that were likely to be Iron Age were known (figure 5.1). Twelve months later reminders were sent out to the heritage bodies and all the respondents to the initial enquiry.

Originally the plan was to visit at least ten archaeological sites each year to collect new archaeomagnetic samples, particularly as initial canvassing of professional and amateur archaeologists over the winter months of 2007/8 had yielded such a positive response. Unfortunately, the recent economic downturn meant that many housing or infrastructure projects were either put on hold or cancelled. Furthermore, most council run excavations were cancelled, because monies were redistributed. Regardless, over the period October 2007 to September 2010, some excavations did go ahead and yielded suitable features, making it possible to obtain new magnetic directions. In total eleven sites were visited and 25 new features were sampled for archaeomagnetic investigations (table 5.1), and details of these are presented in section 5.3.



*Figure 5.1: Location map showing all of the excavations on potential Iron Age sites planned for the period October 2007-November 2009 (red) and those visited during this research (green).*

### 5.1.2 Sampling rationale

In order to be of use to this project and given the degree of positive response to the canvassing of professional and amateur archaeologists, sites were only visited if the feature to be investigated was part of an area suspected to contain Iron Age occupation. Two sites were turned down because the features to be sampled were unquestionably late Roman but were on a multiperiod site, which extended back into prehistory. For those sites that were visited, all of the criteria for archaeomagnetic directional dating were observed (section 5.2.1). This approach led to one site in Winchester not being sampled, as the feature in question was an ash dump, so was neither heated *in situ* nor undisturbed since last heating (section 3.5.3). Once collected and processed in the laboratory these new magnetic data would be incorporated into the revised British database, thus requiring that high quality magnetic directions were obtained. The next section will describe the processes utilised to sample and analyse the material collected from these heated features.

### 5.2 Archaeomagnetic dating technique

This section will describe the procedures employed in this project for sample collection, measurement and processing and the entire process is presented visually in figures 5.2, 5.3 and 5.8. The sampling procedure employed in this study follows the method utilised by most UK practitioners (Linford 2006: 7). It is generally accepted that the factors controlling the consistency of directions are variable, but can cause deflections in the magnetic direction up to 8° (Tarling *et al.* 1986). The implication of this potential error is that careful archaeomagnetic sampling is essential to produce good quality data, as it should be possible to determine the directions of individual samples to within 2-3° (Linford 2006: 9). Some of the most common factors that can cause the variation in direction to be greater than 3° can be minimised through a combination of meticulous recording and considered sampling strategies, tailored to the specifics of each set of material to be sampled. The following is a description of the entire process employed during the fieldwork

aspect of this project from sample collection through to statistical analysis of the remanent directions.

Site	Location	Number of features sampled	Feature
Bamburgh Castle	Northumberland	1	Kiln
Birnie	Moray	2	Kiln
			Kiln
Castlehill	Midlothian	2	Hearth
			Hearth
Kidlandlee	Northumberland	1	Hearth
Market Deeping	Lincolnshire	2	Fire pit
			Hearth
Mellor	Cheshire	1	Hearth
Poulton-le-Flyde	Lancashire	3	Hearth
			Burnt soil
			Burnt soil
Sadlers End	Berkshire	1	Furnace
Street House	North Yorkshire	2	Hearth
			Oven
The Cairns	South Ronaldsay, Orkney	6	Floor
			Hearth
			Floor
			Hearth
			Flue?
			Hearth
Tŷ Mawr	Anglesey	3	Hearth
			Hearth
			Hearth

*Table 5.1: The fieldwork activities that have been undertaken during this project.*

### 5.2.1 Sample selection and collection

The collection of samples of heated material from archaeological sites for dating via magnetic direction is a lengthy process, requiring a methodological and considered approach (Lange & Murphy 1990). The procedure employed in this project is outlined in figure 5.2. Initially, it is necessary to examine the feature to identify if there are any obvious signs of slumping or disturbance since the last firing event, and to ensure that the feature has probably experienced sufficiently elevated temperatures to enable the ambient geomagnetic field to be recorded. As a general guide, the colour and texture of the material is used to inform this decision, with the presence of reddened, hardened or vitrified material being good indicators. Next, the area in the immediate vicinity of the feature is checked for magnetic anomalies. Typically, this can be done by putting a string line over the feature and carefully moving a magnetic compass along the string, keeping it horizontal to the ground surface and watching for any deviations in the compass needle. At this stage, the site director is generally consulted to identify if there are any issues with removing any parts of the feature and to ensure that other workers in the vicinity are aware to work away from the feature during sampling.

Once satisfied that the material is undisturbed and well fired the sampling process begins by recording details on the texture, colour, clay content and moisture levels of the material to be sampled, photographing and making a sketch plan of the feature. Then the sampling locations are decided and samples are only collected from material that on initial inspection appeared to be physically stable, un-weathered and homogeneous. The field guide for the latter was to sample areas of the same colour and avoid mottled areas, where possible. Furthermore, the edges of features and areas that may have been subjected to different heating conditions, typically identified through the degree of colour change, were also avoided. It is also necessary to identify the location of the areas of fastest cooling and to sample these preferentially, along with material of a similar composition, i.e. without any stones or ceramics material. The samples are distributed as uniformly as possible across the surface of each feature, to obtain a representative sample of



fired material. Generally, between 10 and 20 samples from each feature were collected to enable the identification of any random perturbations in the recorded magnetisation and to provide statistically valid results (Tarling 1983: 140). It is also felt that this approach of sampling across the entire feature avoids any possible effects on the direction due to refraction (Lanos *et al.* 1999).

After the sample locations have been identified, a final step before collection is that the surface of each collection area is prepared by gentle cleaning with a leaf trowel to remove any surface material and to ensure that the area to be sampled is as flat and as level as possible. For well consolidated features a horizontally levelled plastic disc is attached, with epoxy resin, at the sampling position; this method was used at Street House, Ty Mawr, Kidlandlee, Market Deeping, Sadlers End, The Cairns and Birnie. A bull's eye spirit level is used to ensure that the top surface remains horizontal whilst the resin sets (Clark *et al.* 1988). Less well consolidated sediments are encapsulated and sealed within a specially manufactured plastic cylinder, which is pushed into the prepared sampling surface. Again, a bull's eye spirit level is used to ensure that the top surface remains horizontal whilst the tube is pressed into the material; this method was used at Bamburgh Castle, The Cairns, Mellor, Poulton-le-Fylde and Castlehill. At this stage the exact sampling locations are recorded via a second set of sketch plans and photographs. Although it is possible to correct for any observed deformation in the feature, as applied at Maiden Castle, Dorset, UK (Clark in Sharples 1991) and Laprade, French Rhône valley (Hedley & Billaud 2002), the general approach taken in this project was to only collect samples from material that appeared to be undisturbed.

### **5.2.2 Field orientation and sample removal**

For most of the samples collected, orientation in the field was performed using a magnetic compass. This method was used due to the inclement weather experienced during most of the field visits. However, the area around the

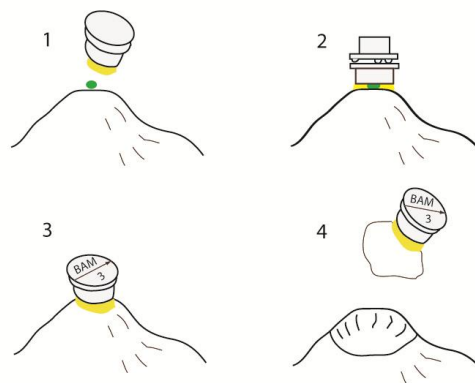
immediate vicinity of the sampling location had already been checked for any magnetic anomalies that may adversely affect the use of a magnetic compass and none were identified at any of the sites visited. Before each sample was removed from the feature, the orientation of magnetic north at site was marked on the top horizontal surface of each sample using a magnetic compass. For all the sites visited, a series of samples were collected from each feature, the only exception being the site of Birnie where for two of the three features sampled (AM159 and AM160) specimens were taken in the laboratory using a reference orientation that had been marked on using a magnetic compass before the entire feature was lifted intact and removed from site. This latter approach was because there was insufficient time to take a complete set of samples from all of the available features.

Once the epoxy resin had set, samples were removed with a trowel and carefully packed in non-magnetic materials for transport to the laboratory at the University of Bradford. On return to the laboratory the samples were trimmed to 2.5cm diameter and 2.25 cm height, so they could fit into the sample holders in the equipment used to measure them. If the material was friable, or particularly dry and brittle, the material was consolidated in 10% polyvinyl acetate in acetone solution to ensure that they did not fragment during measurement. This is done by dissolving 10g of polyvinyl acetate crystals in 100ml of acetone to form a viscous mixture. Holding each sample by the plastic disc, the sampled material is submerged gently into the mixture and held there until no more air bubbles can be seen to escape from the material. With particularly fragile material the polyvinyl acetate solution is carefully introduced to the sample using a pipette until the entire exposed surface is covered. Before measurement all specimens were stored in random orientations, so that any viscous magnetic signal that was acquired during transport or storage would also be random relative to the fiducial north arrow mark on each sample.

## Stage 1: Field work, sample collection



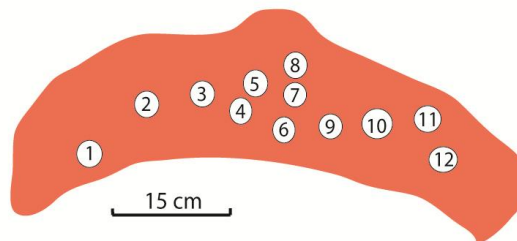
A heated feature potentially undisturbed since last heating is revealed during excavations. The top of the kiln wall can be seen arcing between the two ranging rods.



Orientated and horizontal samples are collected across the heated feature following established protocols (redrawn from Clark et al. 1988)

**Error source = operator, errors of orientation and slumping**

**Precision =  $<2.0^\circ$  (Hathaway & Krause 1990)**



Sampling locations across the heat affected area are carefully recorded before samples are removed



Figure 5.2: The sampling process, highlighting where additional errors due to the individual collecting the samples may potentially occur; the site in this example is Bamburgh Castle.

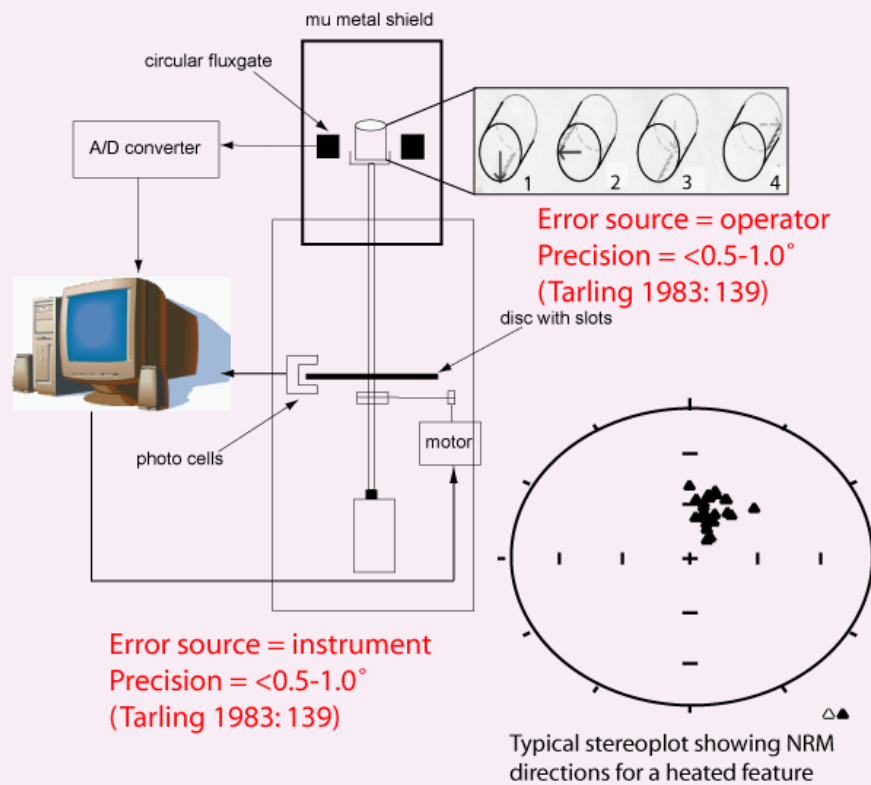
### **5.2.3 Laboratory preparation and measurement of samples**

The magnetisations of all of the samples were measured individually using a Molspin fluxgate spinner magnetometer (Molyneux 1971) at the University of Bradford. The sample is placed into a holder on top of a vertically rotating shaft in the centre of a ring-shaped fluxgate sensor and the entire assemblage is housed within a magnetically shielded chamber to exclude external magnetic fields. This equipment exploits Faraday's law of induction, whereby as the sample is rotated, its remanent magnetisation induces an electromagnetic force resulting in an AC output voltage (Harold 1960b). The magnetometer is computer controlled and requires calibration with a 2cm x 2cm standard before each series of measurements so that the phase and amplitude of magnetisation in the measuring plane could be determined by fast Fourier analysis. The magnetism of the rotating sample is measured by a fluxgate sensor; however, the position of the fluxgate sensor within the instrument means that the induced signal amplitude only depends on the remanence component in the plane of measurement. Therefore, each sample must be measured in four orientations at right angles to each other and in two orthogonal planes, relative to the fiducial mark on each sample, so that the phase and amplitude induced by the entire sample volume can be measured (Walden 1999). This ensured that the net magnetic direction recorded within the sample matrix was determined. If a sample displayed low magnetic intensity, for example as seen at Tŷ Mawr or Poulton-le-Fylde, the number of revolutions per measurement was increased to improve the sensitivity of the instrument (Evans & Heller 2003: 56). From these data it is possible to calculate the three-dimensional remanence vector, which is expressed as declination and inclination with respect to the reference north marked on each sample (figure 3.3).

### **5.2.4 Demagnetisation methods**

Once this natural remanent magnetisation (NRM) has been measured a selection of samples generally undergo complete demagnetisation to test the stability of the vectors in the NRM (figure 5.3). If the vectors are found to be

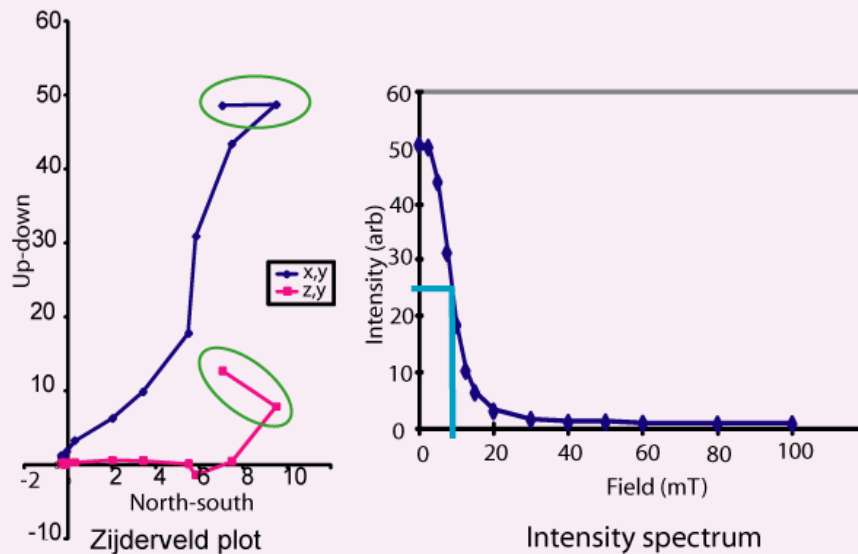
## Stage 2: Laboratory work, sample processing



## Quality assessment

This plot shows that the viscous overprint, circled in green, can be removed by cleaning the signal via bulk demagnetisation at 2.5mT.

The median destructive field, highlighted in blue, is 10mT. This suggests that the magnetic mineralogy is predominately ferrimagnetic and most likely magnetite.



Pilot Demagnetisation of sample AM130/3

Figure 5.3: The procedures undertaken during laboratory processing of samples and where potential sources of error may be introduced. Data shown are from Bamburgh Castle.

unstable then the direction is considered to be unreliable. This process can also detect the possibility of a reheating event, as a re-heating event may mask the direction acquired during the heating event of archaeological interest, particularly if the second heating was to an elevated but lower temperature. Furthermore, if magnetic material is left undisturbed for any period of time it can acquire a viscous remanent magnetisation (VRM; section 3.5.1). As with a reheating event, this new remanence can partially overprint the NRM, distorting the signal measured in the laboratory. The underlying principal for VRM acquisition is that grains with lower relaxation times (section 3.5) are more likely to carry a secondary magnetisation. This is because they are more likely to have lower anisotropic energies such that their directions are more easily randomised and they tend to track the direction of the ambient field (Dunlop & Özdemir 1997: 275). By exploiting this feature it is possible to identify, isolate and remove the viscous signal without affecting the primary magnetisation of archaeological interest or characteristic remanent magnetisation (ChRM) (Zijderveld 1967).

There are two main methods by which the VRM can be identified and separated from the ChRM: alternating field (A.F.) and thermal demagnetisation. The basis behind A.F. demagnetisation is that magnetic components with short relaxation times will also have low coercivities, whereas with thermal demagnetisation these components have lower blocking temperatures (Dunlop & Özdemir 1997: 275; Tauxe 2002: 96). Thermal demagnetisation involves successive heating-cooling cycles, to a predetermined maximum temperature each cycle. This technique requires good temperature control, and more importantly, good control of the external field as it is essential that the samples cool in zero external magnetic field, to ensure that the components with the lower blocking temperatures are randomised so do not contribute to the observed remanence (Tarling 1983: 90). The main problem with this technique is that many minerals present in geological materials decompose during heating and form new magnetic minerals. In order to examine the chemical stability of the sample during incremental thermal demagnetisation the susceptibility of the sample is monitored because any change

is this parameter will indicate a change in the magnetic mineralogy. The main benefit with thermal demagnetisation is that the magnetisation is being removed in the same manner as it was originally acquired.

In the laboratory at the University of Bradford all demagnetisation was done using A.F. demagnetisation. This technique was used because plastic buttons and tubes were used for sample collection in the field, with a PVA solution used for consolidation, and these materials would not tolerate repeated heating. Furthermore, A.F. demagnetisation does not cause any chemical changes to the sample material and allows for comparatively rapid analysis of samples. The samples are tumbled within an alternating field (A.F.) whose strength is greater than the coercivity of the domains carrying the remanence to be removed. As it is the least stable magnetic domains, with the shortest relaxation times, that are responsible for VRM (Tauxe 2002: 56). The theory is that magnetic directions of domains with low coercivities and hence low relaxation times will move to track the alternations of an A.F., causing them to become randomised as the peak strength of the A.F. is slowly reduced to zero. As the sample is tumbled over two axes it results in 98% of the magnetic domains within the sample being presented to the applied field (Hutchings 1967). By incrementally increasing the A.F. over a specimen tumbling within a magnetically shielded chamber (to cancel out the ambient field) it is possible to separate out the different components of the remanence of a sample.

In order to determine the appropriate strength of A.F. required to remove the VRM signal, the magnetisations of at least 25% of the total number of samples collected were selected to be pilot samples for complete demagnetisation. Generally, the intensities were examined and samples displaying the highest, lowest and typical intensities were selected for pilot demagnetisation. Also, by plotting the NRM vectors on a stereoplot (figure 5.4), it is possible to identify samples

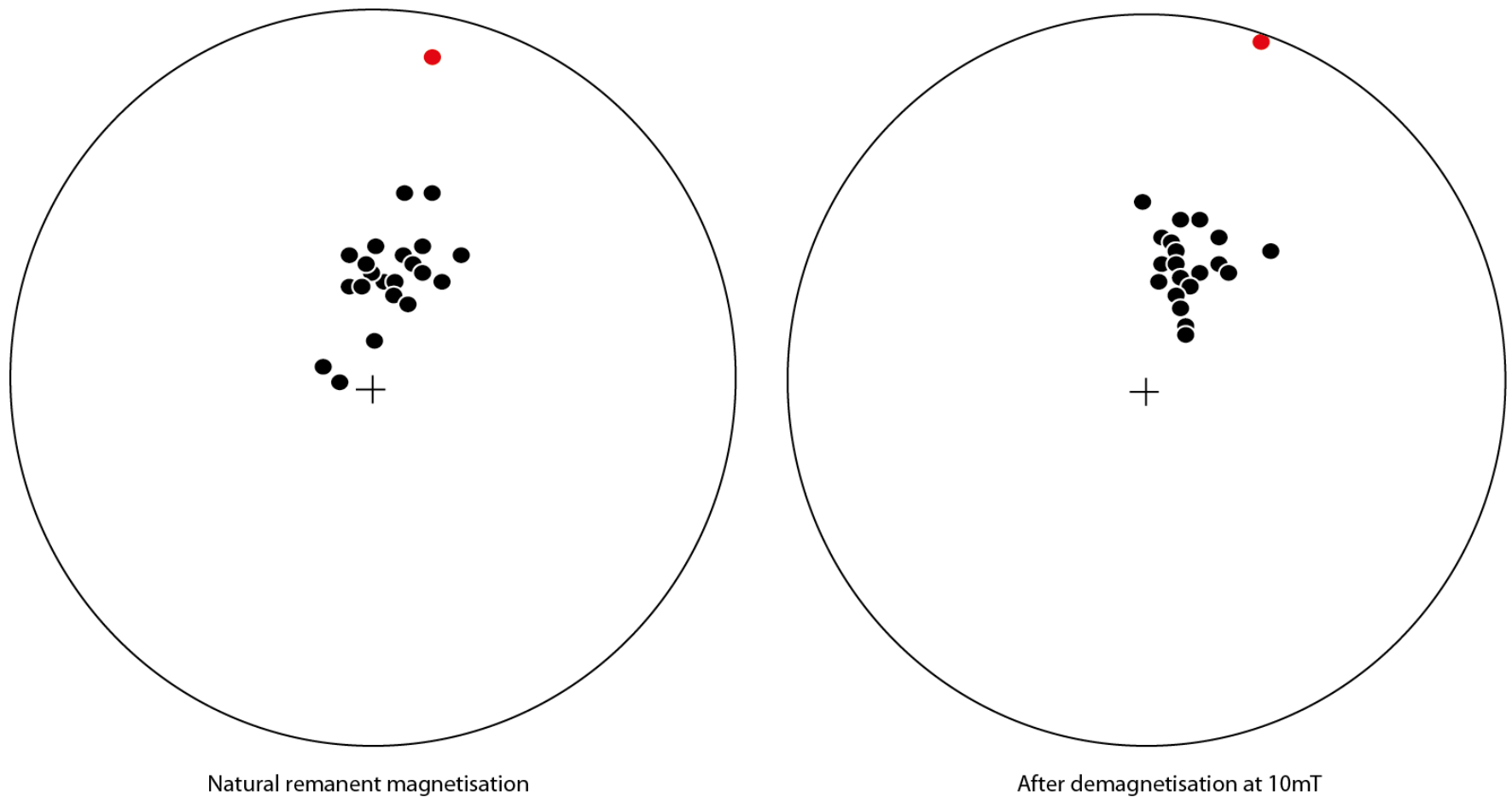


Figure 5.4: A series of stereoplots demonstrating the effect of cleaning the magnetic signal using A.F. demagnetisation. The data presented here are from Bamburgh Castle, AM130. Each circle represents an individual sample with closed circles representing positive inclinations and open circles representing negative inclinations. Note how the overall grouping improves due to the demagnetisation, but a potential outlier shown in red remains separate.



representative of the NRM grouping and any potential outliers. Where possible a combination of each was selected. The magnetic signal of these pilot samples were investigated by stepwise demagnetisation in fields of 2.5, 5, 7.5, 10, 15, 20, 25, 30, 40, 50, 60, 80 and 100mT (peak applied field), with the remanence re-measured after each step in the Molspin fluxgate spinner magnetometer (Walden 1999). For the samples processed during this project the process of pilot demagnetisation generally aimed to identify and remove the viscous component without destroying the characteristic remanence (ChRM).

Although A.F. demagnetisation does not induce any chemical changes to the sample, it is possible that the application of this method can fail to completely demagnetise the remanence of the samples. AF demagnetisation is particularly effective at removing remanence carried by multi-domain grains, but not single domains or pseudo-single domain grains (Butler 1992: 82). This possibility is monitored throughout the laboratory procedure through the construction of intensity spectra (figure 5.5). These spectra only provide an indication of the magnetic mineralogy of the pilot samples via a qualitative assessment of the relative “hardness” of the magnetic signal. “Hard” magnetic signals generally indicate that the matrix is predominately single domain magnetite and is characterised by the intensity of magnetism only being reduced by higher A.F., whereas the distinctive feature of “soft” signals are when the magnetic intensity is reduced at lower A.F. The “soft” magnetic signal suggests that the magnetic matrix is predominately multi-domain magnetite. In order to provide a visual representation of the consistency of the magnetic direction during demagnetisation the remanence vector components (x, y, z) left after each demagnetisation step are plotted on a Zijderveld diagram (Zijderveld 1967); (figure 5.6). This plot reveals the number of magnetic components present in the signal and in archaeological samples there are typically two: the TRM and the VRM signal (Zijderveld 1967).

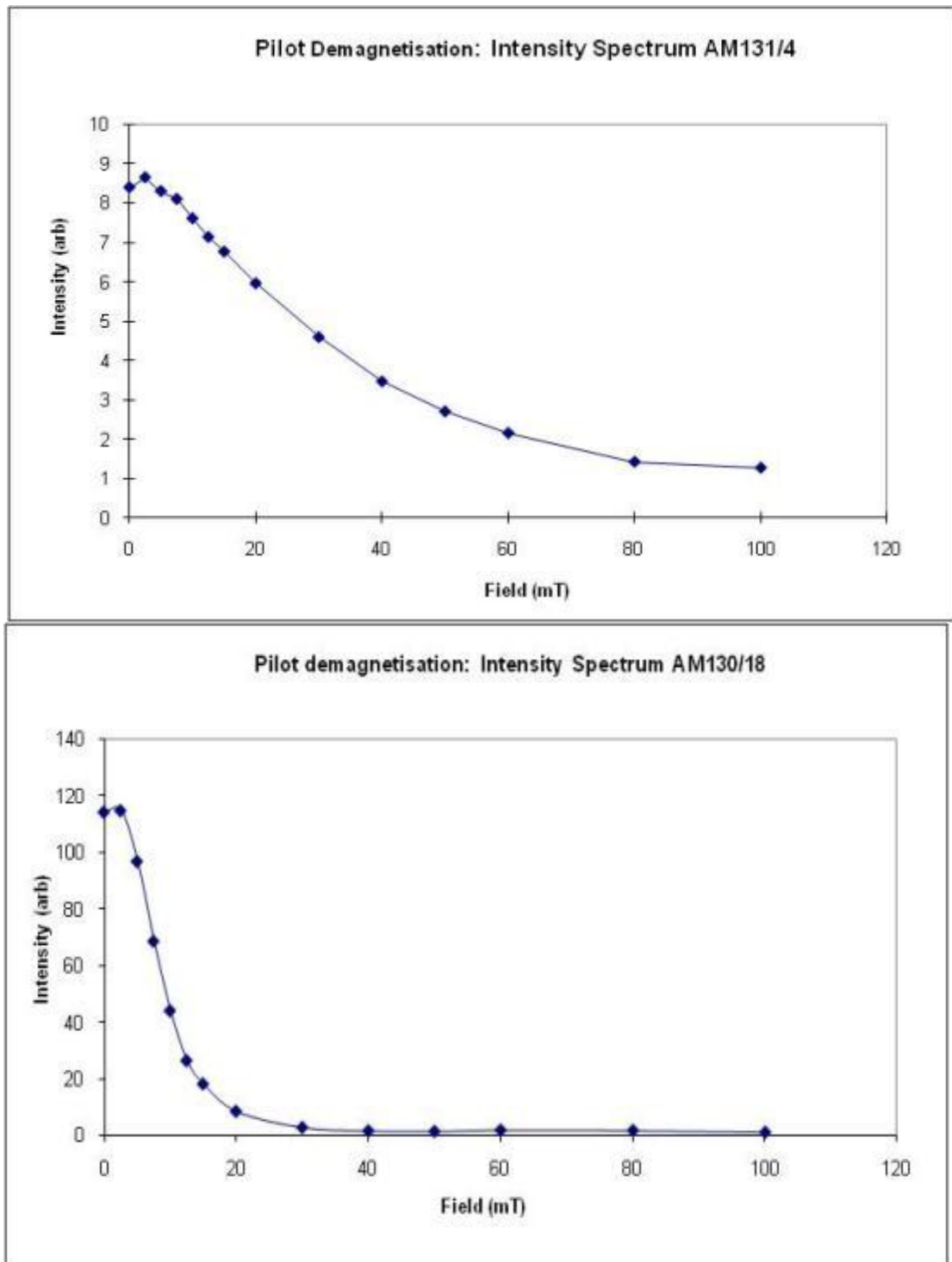


Figure 5.5: Example intensity spectra showing responses typical for signals that indicate the presence of predominately hard (top) and soft (bottom) magnetic minerals. Top is an example spectrum from Kidlandlee (AM131/4) showing a high proportion of haematite present in the matrix. Bottom is from Bamburgh Castle (AM130/18) showing a spectrum typical of a matrix that is predominately magnetite.

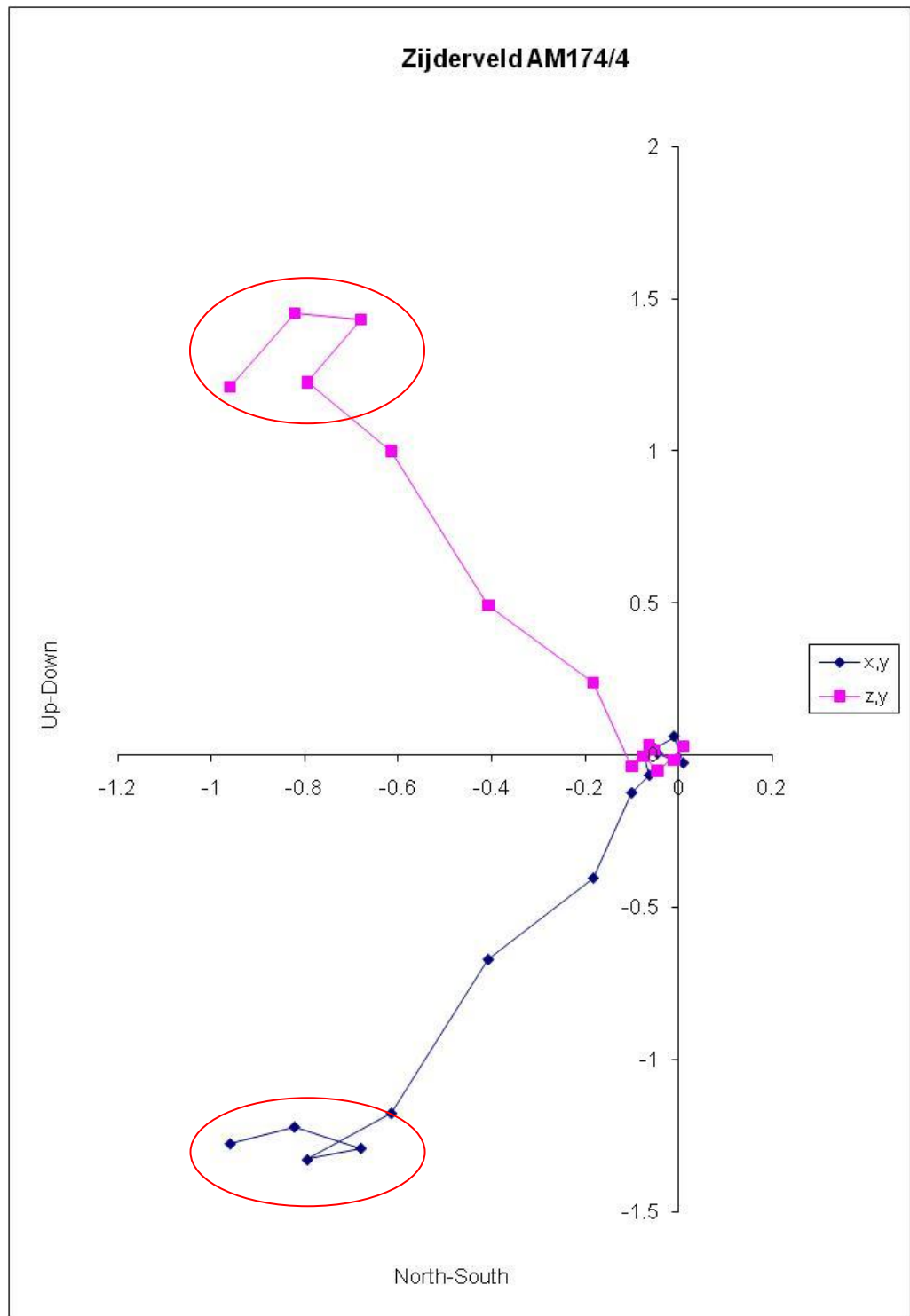


Figure 5.6: Example Zijderveld plot showing how the magnetic vector alters as the less stable components are removed until no magnetism is left at 100mT, demonstrated as all three components tend to zero. This example is from Market Deeping and clearly shows the change in direction as the viscous component to the direction is removed at 7.5mT, circled in red.

Further details on the stability of individual vectors can be supplied by two simple calculations: the median destructive field (MDF) and the percentage of the original intensity remaining at 100mT. Both of these parameters provide a qualitative assessment of the relative proportion of magnetic minerals present within the sample and help to describe the results from the intensity spectra. The MDF is simply the level of demagnetisation required to reduce the magnetisation of the sample to half its original value, whereas the percentage remaining of original intensity is calculated by:  $(\text{intensity at 100mT} / \text{NRM intensity}) \times 100$ . Higher values correspond to more “hard” magnetic signals, which are consistent with a relatively higher proportion of haematite present within the sample matrix. Bamburgh Castle (AM130) and Street House (AM132) are examples with a softer magnetic signal, displaying lower MDF and percentage remaining at 100mT (tables 5.3 and 5.28). While Kidlandlee (AM131) and Mellor (AM134) are examples displaying a harder magnetic signal with higher MDF and percentage remaining at 100mT (tables 5.13 and 5.19). So, from a study of the pilot sample behaviour as presented in Zijderveld diagrams and intensity spectra, the A.F. strength can be chosen that provides the optimum removal of less stable components, leaving the magnetisation of archaeological interest. This A.F. would then be applied to all of the remaining samples in a bulk demagnetisation and the remanences re-measured (figure 5.7) to provide the ChRM. The MDF and the percentage of the initial intensity remaining at 100mT provide an indication of the stability of the individual remanence and so the reliability of the mean magnetic direction.

Finally, to provide an indication of the validity of the results produced the demagnetisation data from the pilot demagnetisation are also assessed using methods defined by Tarling and Symons (1967) to provide an indication of the magnetic stability, the stability index (SI). Although there are other methods available, for example the Briden index (Briden 1972) and PSI (Stupavsky & Symons 1978), the SI was chosen as it is most sensitive to the changes in directional stability (Tarling 1983: 133f). The other methods provide a measure of how the NRM

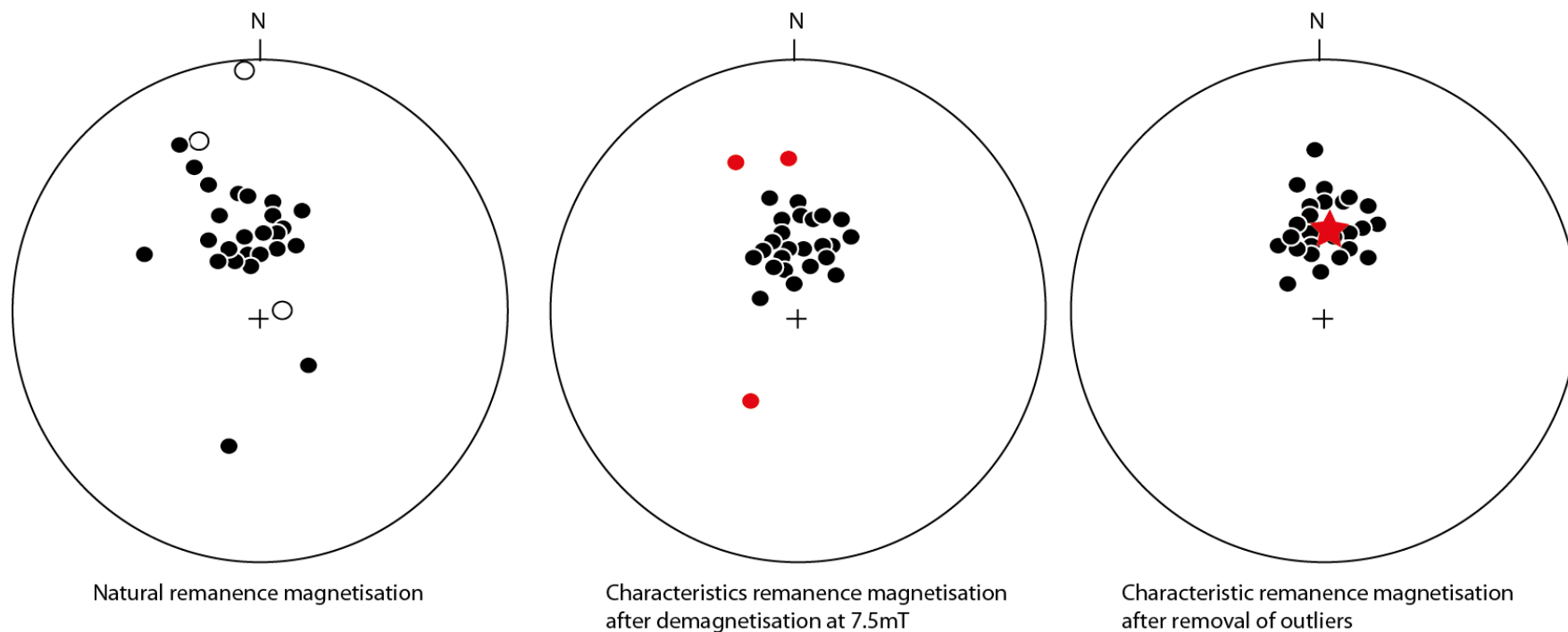


Figure 5.7: A series of stereoplots demonstrating the effect of cleaning the magnetic signal using A.F. demagnetisation and the statistical analysis of the data, to determine if all of the samples recorded the same magnetic moment. The data presented here are from The Cairns, AM163, and after magnetic cleaning three potential outliers were detected, shown in red. Each circle represents an individual sample with closed circles representing positive inclinations and open circles representing negative inclinations. The red star represents the mean direction for AM163 after removing outliers and it is this mean direction that is relocated to Meriden ( $\gamma = 52.43^\circ$   $\lambda = -1.62^\circ$ ) before calibration.

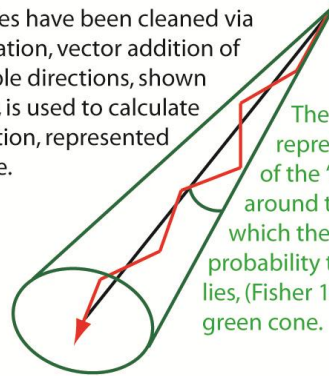
intensity of the samples changes during demagnetisation and, whilst informative, for the current application of archaeomagnetic data it was more important to define the directions of the vector, making the SI method more appropriate as it is based on the consistency of the magnetic direction over the successive incremental demagnetisation steps. Therefore, SI provides an objective assessment of the stability of the magnetic signal, as stable signals tend to show the lowest scatter over the widest range of demagnetising treatment, in this case A.F. Thus Stability Index (SI) = maximum (circular standard deviation/range of treatment<sup>2</sup>). The results have been formalised by classifying them into the following categories: <1 unstable; 1-2 metastable; 2-5 stable; >5 very stable (Tarling & Symons 1967). It is recommended that the maximum value is quoted as the SI; however, the SI quoted for each archaeomagnetic direction in this research was calculated for the remaining magnetic signal or ChRM. Therefore, if a bulk demagnetisation was carried out at 5mT, the SI quoted was calculated using the successive magnetic directions from the pilot demagnetisations covering the range 5mT to 100mT. This form of analysis is based solely on directional changes and only provides an indication of how well each vector has been defined. It is subjective and only defines the most stably magnetised vector, that is dominant over three or more successive demagnetisation steps, so is prone to be confused by noisy demagnetisation data, but it appears to provide a useful estimate on the reliability of ChRM directions when applied to archaeological samples, because they tend to have only two components to the magnetic signal with only a small viscous component.

### **5.2.5 Statistical analysis**

Once the remanent magnetic signal has been cleaned and its stability has been determined, the next process was to examine whether all of the samples have recorded the same magnetic moment, summarised in figure 5.8. First the data set was summarised and, as magnetic data are three dimensional, a theoretic distribution and accompanying series of statistical procedures developed by Fisher (Fisher 1953) for points distributed on a sphere was employed. This procedure

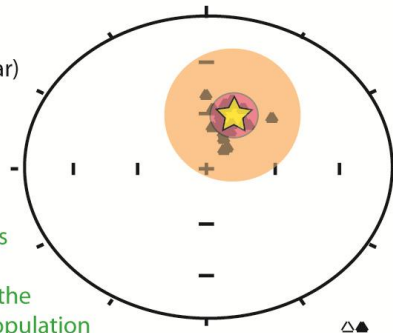
## Stage 3: Statistical Analysis and Relocation

After the samples have been cleaned via AF demagnetisation, vector addition of individual sample directions, shown by the red lines, is used to calculate the mean direction, represented by the black line.

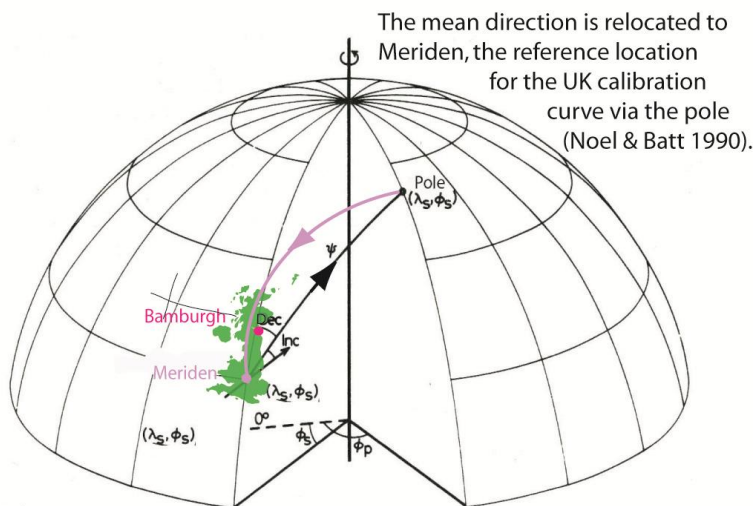


The alpha-95 statistic represents the semi angle of the 'cone of confidence' around the mean within in which there is a 95% probability that the true direction lies, (Fisher 1953) shown here as the green cone.

The mean direction (yellow star) and alpha-95 (pink circle) as plotted over the sample population.



The discordancy test calculates the angle of a Fisherian distribution which represents the 95% confidence limit of the population from the samples were drawn represented by the mean direction (McFadden & McElhinny 2000). This is displayed as the orange circle centred over the mean direction and in this case shows that there are no outliers.



The mean direction is relocated to Meriden, the reference location for the UK calibration curve via the pole (Noel & Batt 1990).

Corrected Mean Declination: 15.7  
Corrected Mean Inclination: 58.3  
Alpha-95: 3.8

Figure 5.8: A series of images to illustrate the theory behind the statistical analyses and data manipulation carried out on the results from the laboratory work.

results in the calculation of a mean declination, mean inclination and  $\alpha_{95}$  value as described in section 3.3 for the ChRM. In this case it represents the magnetism of archaeological interest after the removal of any spurious signals due to the presence of unstable magnetic grains. The mean remanent direction is essentially a unit vector addition of the individual sample remanence(s) (equations 9, 10 and 11); the  $\alpha_{95}$  value provides a measure of central tendency (equation 13) and is roughly equivalent in concept to  $2\sigma$  standard deviation in more conventional Gaussian statistics. In the same way  $\alpha_{95}$  provides a confidence limit for the observed mean direction, but requires at least 7 observations to be statistically meaningful (Tarling 1983: 119), because it depends on  $1/\sqrt{N}$  (Butler 1992: 109).

Although larger  $\alpha_{95}$  values suggest that the mean direction is not well defined, it does not provide a measure of the actual scatter of the vectors (Tarling 1983: 122). Therefore, the samples are also subjected to a discordancy test, which determines if any of the sample directions deviate significantly from the mean and this was set at 95% confidence level. The statistical procedures recommended by McFadden and McElhinny (2000: 92) were employed to identify any outliers at 95% confidence level (Palaeomag-Tools version 4.2 provided by Mark Hounslow, Lancaster University), which calculates the angular distance,  $\psi$ , any individual point is from the true mean, represented by the sample mean (figure 5.8). If any point falls further than the  $\alpha_{95}$  from the mean direction it is considered not to be consistent with the sample population and so is considered to be an outlier.

Any point which fell beyond the 95% confidence limits was considered to be discordant, hence not representative of the sample population. If a sample was identified as an outlier during this project a re-examination of the location of that sample on the feature would generally reveal an explanation, e.g. via evidence of potential movement or the sample was from the edge of the heat affected area. When this was the case the sample was eliminated from any further analysis; all features sampled had at least one discordant sample. The more conservative “two-



delta” test (Beck 1983) was also performed as a check that any individual directions were discordant. With this test individual directions are excluded as outliers if they diverge from the mean by more than twice the angular standard deviation of the data set, if the data are Fisherian this is given by equation 15. If the data set is Fisherian and the calculation is repeated with new values for the mean direction,  $N$  and  $R$  (see figure 3.3), no new directions should fail the test. Previous workers have defined an upper limit of  $\alpha_{95}$  of  $5^\circ$  as being appropriate for dating (Clark *et al.* 1988: 606); therefore, if the ChRM of a collection of samples displayed a dispersion greater than  $5^\circ$  it was considered to be highly scattered (figure 5.9).

$$2\Delta = \frac{162^\circ}{\sqrt{k}} \quad \text{Equation 15}$$

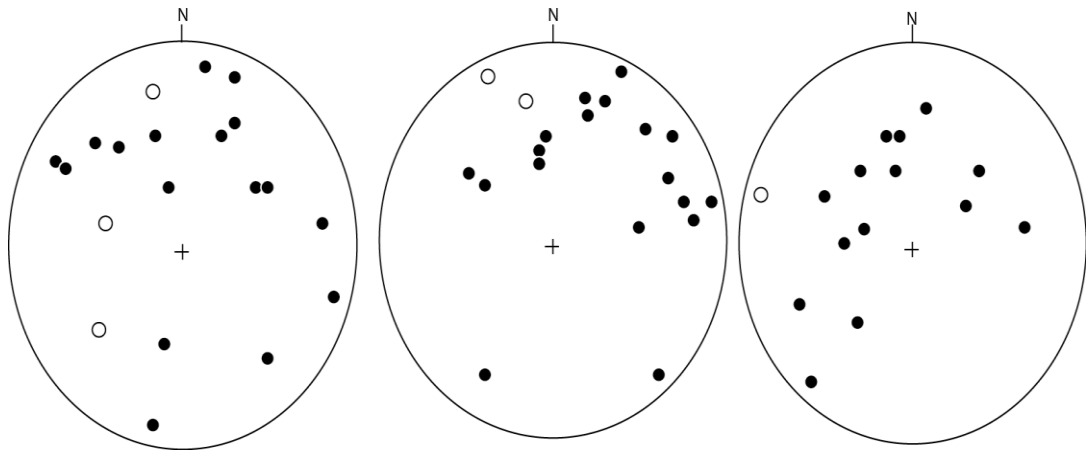


Figure 5.9: A series of stereoplots demonstrating the impact of physical disturbance or weathering (AM82 and AM83), or insufficient heating (AM84), on the measured magnetic signal. Each circle represents an individual sample with closed circles representing positive inclinations and open circles representing negative inclinations. The first two examples are from Tŷ Mawr the other from Poulton AM84. These interpretations on the causes of the scatter in the signal are derived from field observations during sample collection. All data presented are the natural remanence magnetisation.

### 5.2.6 Correction for magnetic variance and relocation

As all the samples in this study were collected using a magnetic compass, it is necessary to apply a correction for the magnetic variation on the date that the samples were collected. The International Association of Geomagnetism provides

information on the components of the magnetic field, based on global observatory data, and can provide an estimate of the variation in the magnetic declination value for a specific date, any time from 1900, anywhere on the globe. The declination calculator employed in this project is available at [www.ngdc.noaa.gov/geomagmodels/Declination.jsp](http://www.ngdc.noaa.gov/geomagmodels/Declination.jsp). Essentially, the value from the declination calculator is added onto the mean declination of the ChRM after any outliers have been removed. The mean remanent direction of the ChRM at this point is only calculated with respect to the reference north and horizontal. Therefore, as a final step, it is necessary to adjust the magnetic direction to account for the longitude and latitude of the sampling location as the dipole geomagnetic field also varies with location on the Earth's surface. This correction is done by calculating a virtual geomagnetic pole (VGP) for the sample (essentially the North Pole position indicated by the mean remanent direction), established taking into account the position of the sampling location on the Earth's surface. From here the magnetic field declination and inclination this VGP would cause at Meriden ( $\phi = 52.43^\circ \text{ N}$ ,  $\lambda = 1.62^\circ \text{ W}$ ), the reference locality for the British SVC, can be computed (Noel & Batt 1990). This is a mathematic transformation so does not change the inherent remanence direction of the sample, just relocates it to enable it to be compared to the British archaeomagnetic SVC (Zananiri *et al.* 2007) in order to provide a date. This series of corrections and transformations are summarised in figure 5.10.

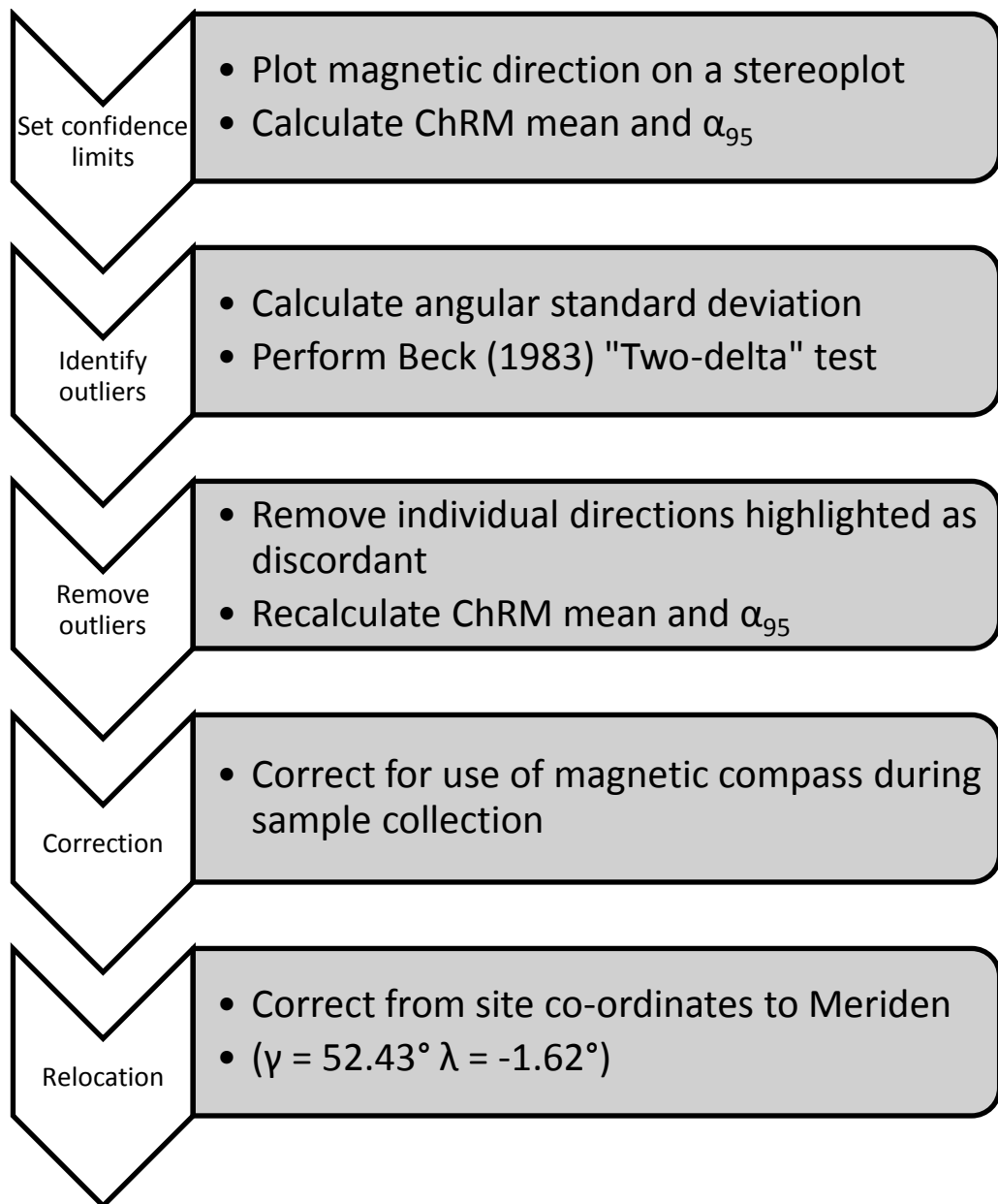


Figure 5.10: Summary of the series of statistical analyses and mathematical procedures that the magnetic direction is subjected to after bulk demagnetisation.

### 5.3 Results of fieldwork

During the period October 2007 to September 2010 a series of fieldwork projects were undertaken to collect samples for more magnetic directions. This section presents the results of the magnetic measurements undertaken, via a summary of each of the sites sampled during the fieldwork aspect of this project. Complete details on the work undertaken are presented in the series of laboratory reports produced for the site director at each site visited, which are included as appendix 3, along with all original data.

### 5.3.1 Bamburgh Castle: AM130

The site of Bamburgh Castle, Northumberland (NU182350) (figure 5.1 on page 140) contains evidence of occupation covering nearly 2000 years (Young 2003). Previous excavations had revealed evidence of prehistoric occupation, but since the excavations reopened in 1996 the earliest evidence recovered so far is late Norman/Anglo-Saxon (Graeme Young, pers. comm. 2008). The feature sampled was located in Trench 1 and appears to be a kiln, positioned at the far northern extent of the West Ward, close to St Oswald's Gate. At the time of sampling the date of the kiln feature was unknown, but it is cut into glacial clay and sealed by both a 14<sup>th</sup> century structure and the exterior wall that formed part of the early defences of the fortress. This suggests that it is pre 14<sup>th</sup> century AD and may be part of a structure that predates the fortress. The kiln was chosen for sampling based on its state of preservation and evidence for firing in antiquity (figures 5.11 and 5.12). The kiln appeared to be circular and only a quarter of the lining was exposed for sampling. The exposed lining was approximately 10cm thick and constructed of clay. The clay showed evidence of being heated, but was heavily mottled, with the colour ranging from dark reddish brown to red (Munsell references 2.5YR 2.5/3, 3/2, 3/3, 2.5/4, 3/4, 4/4 and 4/6). The kiln contained a series of fills and its base was not apparent at the time of sampling, such that the walls were sampled. These survived to a height of at least 50cm enabling two layers of samples to be collected down the wall (figure 5.13). It is possible that the bedrock formed the base of the kiln and the clay walls formed a dome, which has since collapsed, leaving only the bottom section of the clay lining *in situ*.



Figure 5.11: AM130; context 1260, at Bamburgh Castle, viewed from the west ( scale 0.15m) showing the exterior wall on the left.

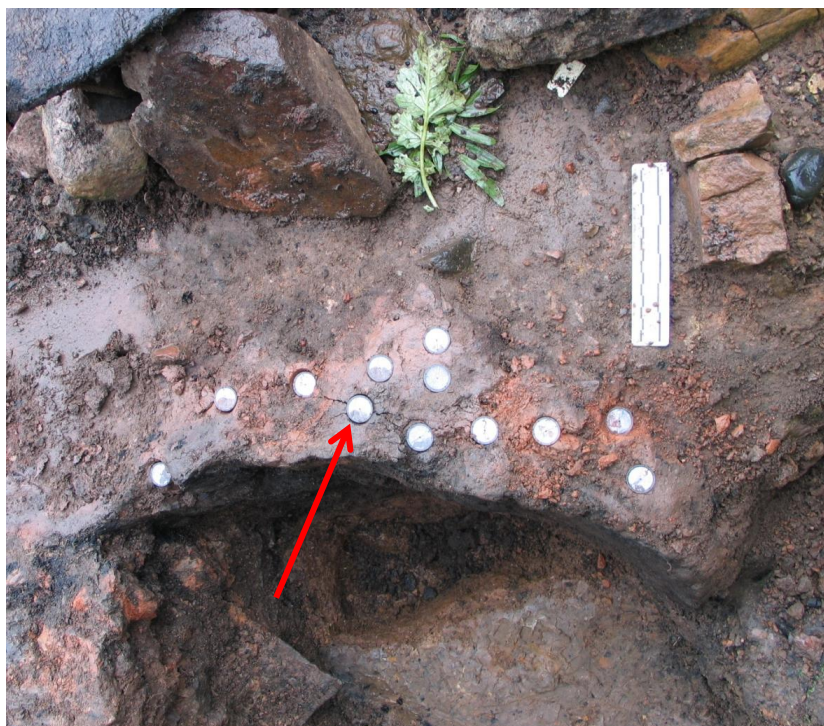


Figure 5.12: AM130; the sampling locations of the first layer across the kiln wall. One sample was found to be an outlier, indicated by the red arrow, and this photo shows the possible cause (note how the wall has cracked and shifted around one of the sampling locations).

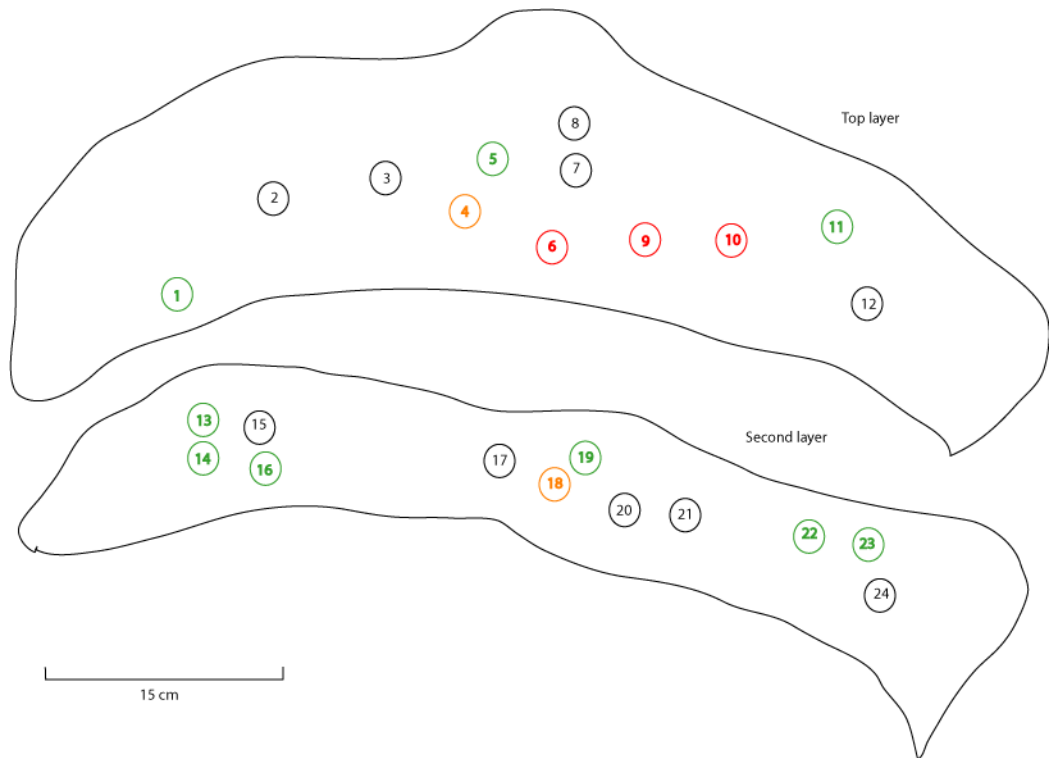


Figure 5.13: AM130, a schematic plan of the kiln wall sampled at Bamburgh Castle showing the location of the samples with intensities over  $200 \times 10^{-6} \text{ Am}^2$  (red),  $200-100 \times 10^{-6} \text{ Am}^2$  (orange), under  $50 \times 10^{-6} \text{ Am}^2$  (green) and under  $20 \times 10^{-6} \text{ Am}^2$  (black). Note how a similar pattern is repeated on both sampling levels.

A total of 24 samples were collected and all of the samples had a measurable remanence, which indicates that the material sampled contained sufficient magnetic minerals to record a stable magnetic direction. However, there were systematic differences observed between the intensities of the materials within the feature, with samples collected from the most easterly and westerly areas of the kiln showing the lowest intensities and the central areas showing the highest; this pattern was repeated in both sampling levels. In this case there does not appear to be any relationship to the colour of the material and its intensity, which suggests that these samples should still be able to produce a reliable archaeomagnetic direction. Analysis of the magnetic data determined that 23 of the samples recorded a consistent and stable magnetic direction (table 5.2). Further analysis of the data revealed that AM130/3 was an outlier (figure 5.14 and table 5.3) and this was probably due to cracking of the material during sampling.

Magnetisation	Mean Dec (°)	Mean Inc (°)	$\alpha_{95}$	N	Demagnetisation field (mT)	No. of discordant samples
NRM	5.87	64.5	6.23	24	10	-
ChRM	19.5	61.0	3.8	23	-	1

Table 5.2: Summary of the mean NRM and ChRM for AM130 from Bamburgh Castle (data are at site co-ordinates).

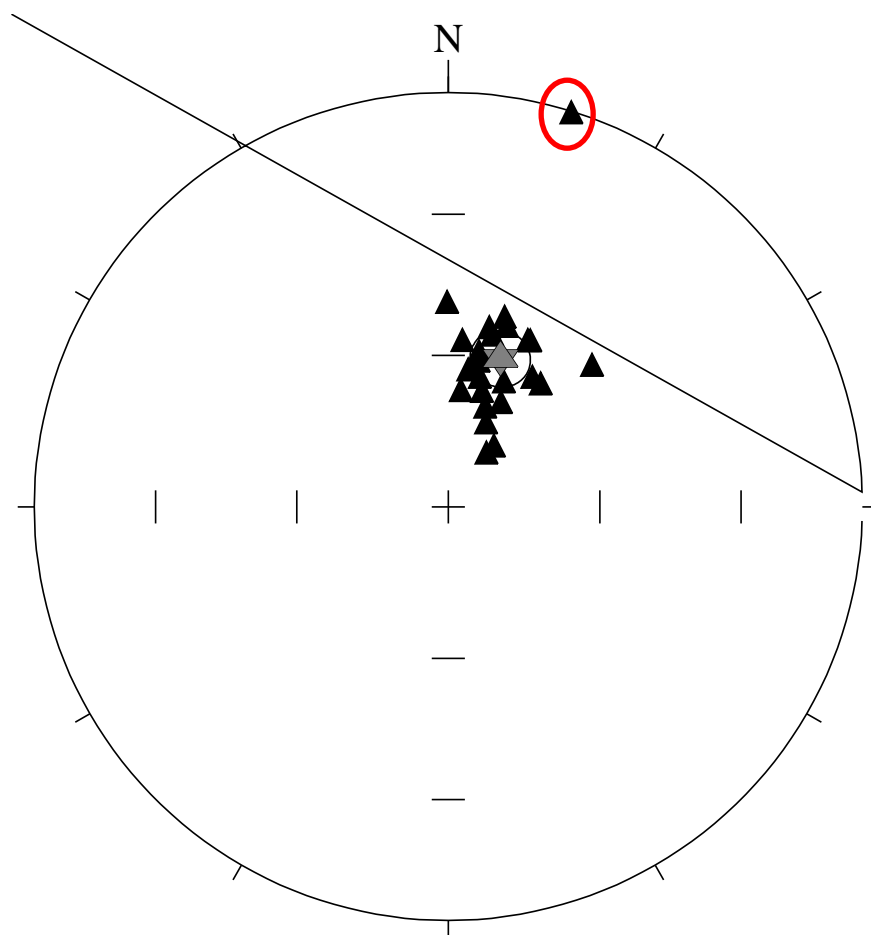


Figure 5.14: Stereoplot showing the ChRM of AM130 from Bamburgh Castle. Closed (open) symbols represent positive (negative) inclinations. In the northern hemisphere inclinations should be positive, so any individual directions with negative inclinations are rejected. The outlier that was removed is highlighted with a red circle. The mean direction (including outlier) is shown by the grey star and the  $\alpha_{95}$  value shown as a circle.



Pilot sample reference	Reason for selecting	MDF (mT)	SI	% intensity remaining at 100mT
AM130/3	Potential outlier, average intensity	8	2, poorly stable	2
AM130/6	Potential outlier, high intensity	12.5	6.4, very stable	4
AM130/8	Representative, average intensity	8	3.5, stable	2
AM130/18	Representative, high intensity	8	4, stable	2
AM130/24	Potential outlier, average intensity	8	2.5, stable	2

*Table 5.3: The results from the pilot demagnetisation of Bamburgh Castle samples to investigate the nature of the magnetic signal.*

### 5.3.2 Birnie: AM87, AM159 and AM160

The site of Birnie is located in the valley of the river Lossie, just south of Elgin, Morayshire (NJ197558) (figure 5.1 on page 140). This site has been investigated since 1998 when two hoards of Roman silver coins were discovered. The site is currently understood to be a later prehistoric settlement with evidence of activity from the Bronze Age, peaking in the Iron Age with continuity to the Pictish period and even Medieval times (Hunter 2007). The features sampled were interpreted as furnaces due to the recovery of slag associated with them in the 2006 field season. These features were located within the boundary of an Iron Age roundhouse which also contained evidence of later medieval activity (figure 5.15). Other than the stratigraphic evidence that the furnaces post-date the roundhouse, and that an earlier furnace was replaced by a later furnace, there was no associated dating evidence. Both of the furnaces in this area were sampled based on their evidence of firing and that they were considered still to be *in situ*. Both furnaces were sampled by David Greenwood in the field on 10<sup>th</sup> September 2007.



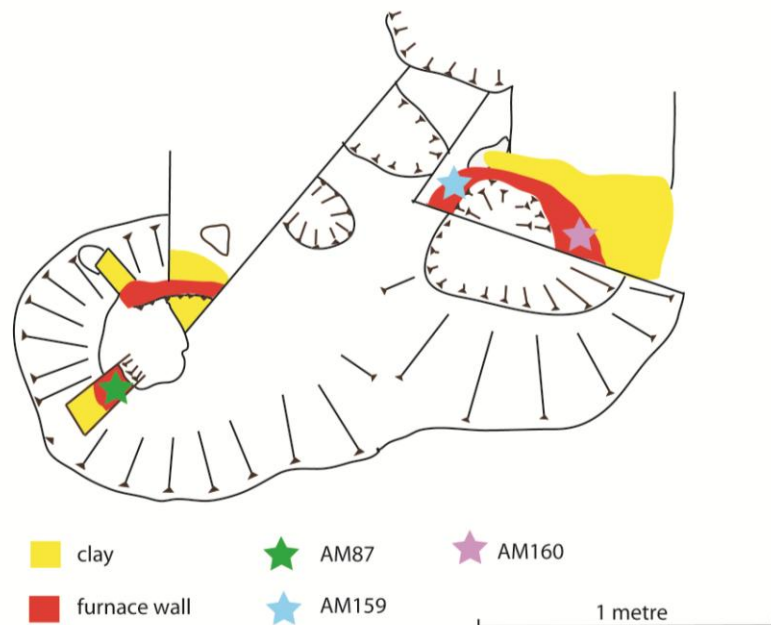


Figure 5.15: Sketch plan of the furnace complex associated with the Iron Age roundhouse at Birnie, viewed from the west. This image has been derived from the excavators' field notes.

#### **AM87 Furnace 1 (Feature 4028)**

Feature 4028 was the youngest furnace and incorporated the northern edge of an earlier furnace (context 4660) in its foundations. The mottled colour of the clay suggested that the clay had experienced some heating in the past and the clay appeared to overlie two large stone slabs and there was a third stone upright within the clay (figure 5.16). There were no clear boundaries to the feature and the mottled colouring and soft texture of clay suggests that this feature may not have been exposed to repeated heating events. The presence of charcoal at the boundary between the clay and the upright stone suggests that the stone was in place during firing. There is also a lens of charcoal on top of the horizontal slabs of stone and sealed by the clay suggesting that this section of the clay wall of the furnace collapsed at some point after last use therefore, it was no longer *in situ* when sampled.



Figure 5.16: AM87, feature 4028, at Birnie, viewed from south-east (scale 1m), showing the sample locations (Photograph © David Greenwood).

Sixteen samples were collected from this feature and all of the samples had a measureable remanence, but there were concerns due to the amount of scatter displayed by the magnetic signals. Analysis of the magnetic data confirmed the observations made from photographs that the material sampled from hearth feature 4028 (AM87) was wall collapse (figure 5.17, tables 5.4 and 5.5). The magnetic signals suggest that the wall was cooling as it was collapsing, so not *in situ*, which is consistent with the archaeological interpretation (Hunter 2007). Five samples displayed negative inclinations and one sample (AM87/18) was found to be discordant.

Magnetisation	Mean Dec (°)	Mean Inc (°)	$\alpha_{95}$	N	Demagnetisation field (mT)	No. of discordant samples
NRM	262.8	63.4	21.7	16	7.5	-
ChRM	293.8	56.3	23.3	10	-	6

Table 5.4: Summary of the mean NRM and ChRM for AM87 from Birnie, data are at site co-ordinates.

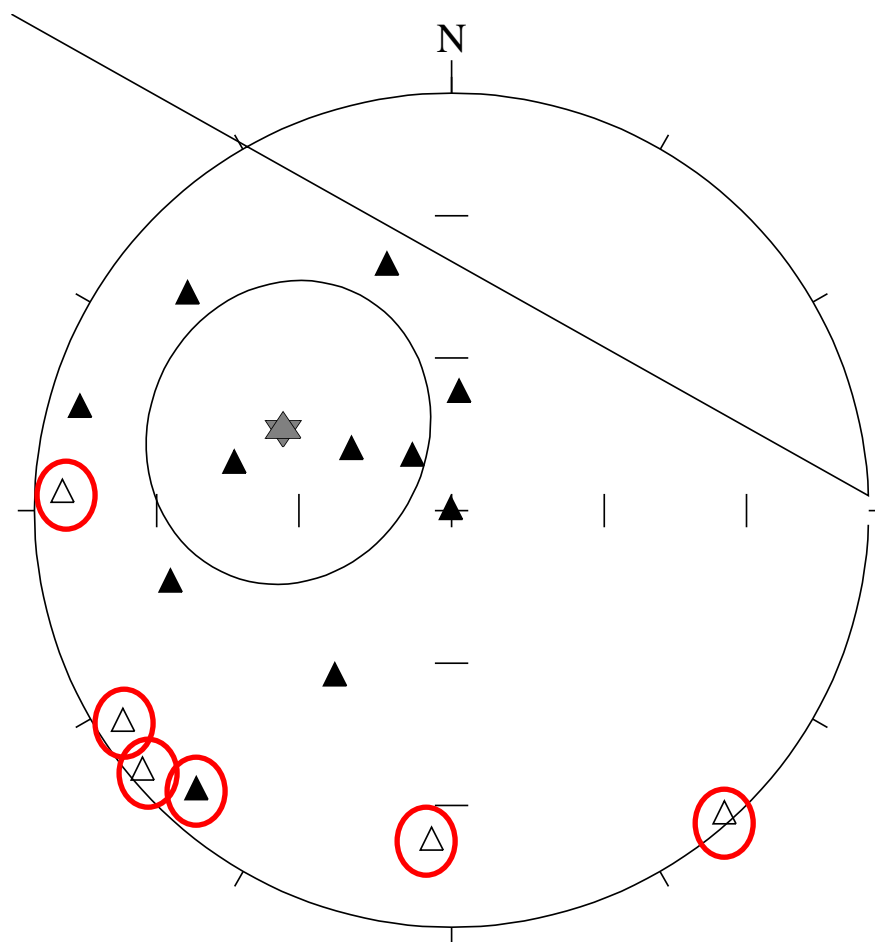


Figure 5.17: Stereoplot showing the ChRM of AM87 from Birnie. Closed (open) symbols represent positive (negative) inclinations. In the northern hemisphere inclinations should be positive, so any individual directions with negative inclinations are rejected. The outliers that were removed are highlighted with red circles. The mean direction (including outliers) is shown by the grey star and the  $\alpha_{95}$  value shown as a circle.

Pilot sample reference	Reason for selecting	MDF (mT)	SI	% intensity remaining at 100mT
AM87/3	Potential outlier, lower intensity	15	2, poorly stable	18
AM87/4	Representative, lower intensity	5	1, poorly stable	6
AM87/7	Representative, high intensity	15	9.7, very stable	5
AM87/18	Potential outlier, high intensity	12.5	1, poorly stable	2

*Table 5.5: The results from the pilot demagnetisation of the samples from feature 4028 at Birnie to investigate the nature of the magnetic signal.*

#### ***Furnace 2 AM159 (Sample 6604) and AM160 (Sample 6605)***

This feature is the earlier of the two furnaces and lies to the south of feature 4028. Two sections of the wall circuit were sampled from this feature: sample 6604 from the northernmost exposed section and sample 6605 from the exposed section of the southern arc of the wall (figures 5.15, 5.18 and 5.19). These wall sections were orientated and sampled separately, but should record similar magnetic directions. However, as the northern section of this feature was incorporated into feature 4028, it is possible that sample 6604 may record the last firing event of feature 4028. David Greenwood placed a reference orientation onto both of the wall sections and lifted these as blocks of material which were transported to the University of Bradford for sampling. Sample 6604, the northern wall section was sub-sampled by Nicola Cowie and sample 6605 sub-sampled by Sarah-Jane Clelland.





Figure 5.18: AM159, sample 6604, from Birnie, showing the sample locations (scale 0.2m)  
(Photograph © Nicola Cowie).



Figure 5.19: AM160, sample 6605, from Birnie, showing the sample locations (scale 0.15m).

With regards to the stratigraphically earlier hearth, 4660, both ends of the hearth were sampled: sample numbers 6604 (AM159) and 6605 (AM160). The NRM data from AM159 showed a lot of scatter (figure 5.20 and table 5.6), but the intensities of the NRM directions were too low to undergo demagnetisation. It is suggested that the material sampled for AM159 was also not *in situ*. Again, this interpretation is consistent with the excavating archaeologist's field notes (Hunter 2007), which suggested that the super structure of the side of the hearth where AM159 was collected had collapsed during the last firing event. Finally, regarding the opposite side of the furnace, analysis of the magnetic data from AM160 (table 5.7 and figure 5.21) and further analysis (table 5.8) determined that only 13 of the 17 samples collected recorded a stable and consistent direction. Two samples had negative inclinations and so were rejected (AM160/5 and AM160/16) and two were found to be discordant (AM160/2 and AM160/9). Therefore, of the three sampling locations from Birnie, only AM160 could provide an archaeomagnetic direction that was likely to reflect the direction of the ambient geomagnetic field during the last cooling event.

<b>Magnetisation</b>	<b>Mean Dec (°)</b>	<b>Mean Inc (°)</b>	<b><math>\alpha_{95}</math></b>	<b>N</b>	<b>Demagnetisation field (mT)</b>	<b>No. of discordant samples</b>
NRM	276.5	39.5	109	24	-	-

*Table 5.6: Summary of the mean NRM for AM159 from Birnie; the magnetic directions showed too much scatter to identify a mean direction (data are at site co-ordinates).*

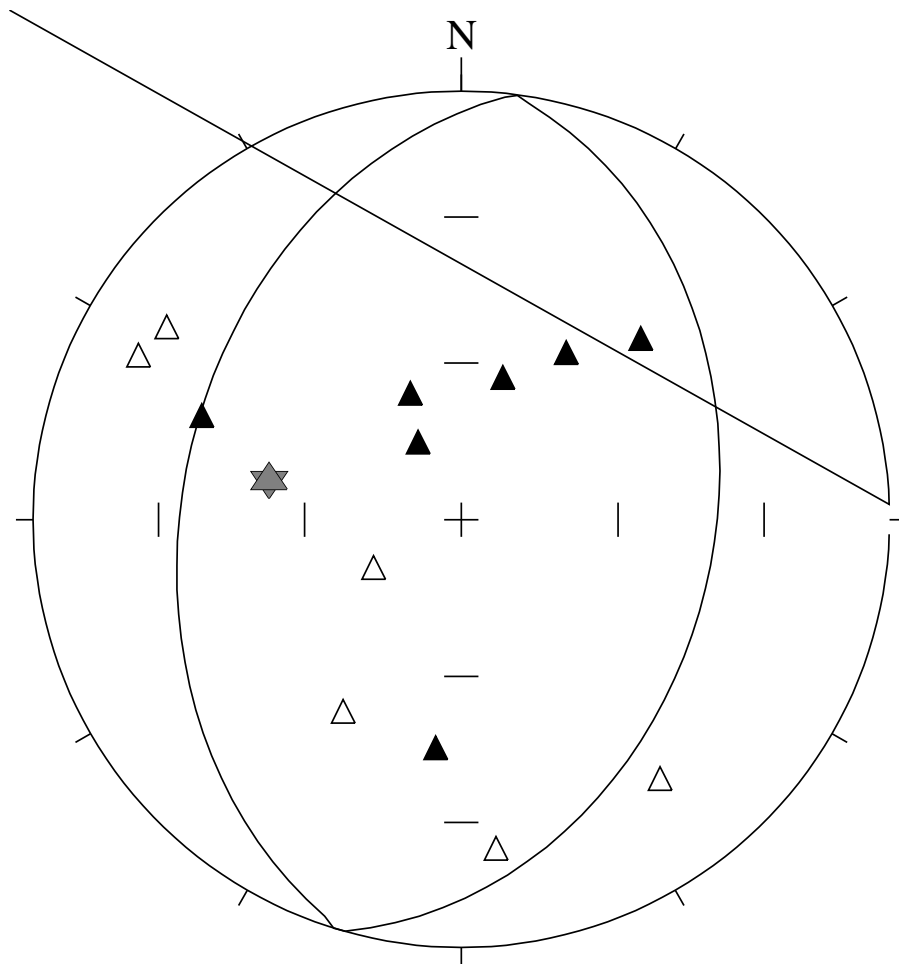


Figure 5.20: Stereoplot showing the NRM of AM159 from Birnie. Closed (open) symbols represent positive (negative) inclinations. In the northern hemisphere inclinations should be positive, so any individual directions with negative inclinations are rejected. The mean direction is shown by the grey star and the  $\alpha_{95}$  value shown as a circle.

Magnetisation	Mean Dec (°)	Mean Inc (°)	$\alpha_{95}$	N	Demagnetisation field (mT)	No. of discordant samples
NRM	331.2	71.2	20.5	17	7.5	-
ChRM	344.0	75.3	5.9	13	-	4

Table 5.7: Summary of the mean NRM and ChRM for AM160 from Birnie; data are at site coordinates.

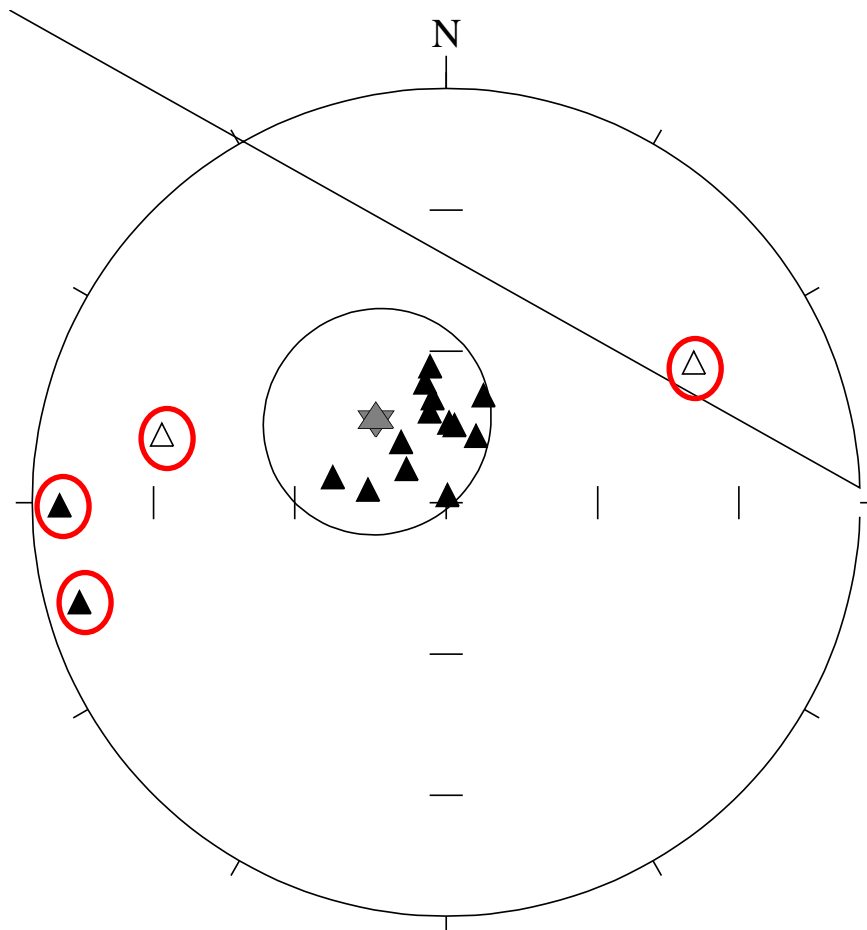


Figure 5.21: Stereoplot showing the ChRM of AM160 from Birnie. Closed (open) symbols represent positive (negative) inclinations. In the northern hemisphere inclinations should be positive, so any individual directions with negative inclinations are rejected. The outliers that were removed are highlighted with red circles. The mean direction (including outliers) is shown by the grey star and the  $\alpha_{95}$  value shown as a circle.

Pilot sample reference	Reason for selecting	MDF (mT)	SI	% intensity remaining at 100mT
AM160/1	Potential outlier, lower intensity	15	2, poorly stable	12
AM160/2	Potential outlier, lower intensity	15	1, poorly stable	12
AM160/8	Representative, high intensity	15	5, stable	1
AM160/12	Representative, high intensity	20	2, poorly stable	4

Table 5.8: The results from the pilot demagnetisation of samples from hearth 6605 at Birnie to investigate the nature of the magnetic signal.



### 5.3.3 Castlehill: AM70 and AM71

The site of Castlehill, Penicuik (NT209587), is on the estate of Sir Robert Clerk in Midlothian, Scotland (figure 5.1 on page 140). This area was targeted for excavation because records in the Old Statistical Account hint at the presence of an Iron Age fort in the locality. Several seasons of excavation have uncovered paved areas and a small selection of stone tools. These structures were dated to the Iron Age based on the recovery of two diagnostic stone tools (David Jones, pers. comm. 2008). A total of two features were chosen for sampling, based on their state of preservation and evidence of firing. Trench 1 (AM70) contained an area of paving that was surrounded by patches rich in charcoal and burnt organics, but there was no evidence for a formal hearth structure (figure 5.22). The paving was set into a sandy matrix, with only a small percentage of clay, but it displayed some evidence of past heating as there was a distinct change in colour, particularly given the proximity of charcoal spreads. It was not possible to sample the paving stones so a large central paving stone was removed to enable the heat affected soil to be sampled and some additional samples were taken from reddened areas immediately adjacent to the paving. The area of paving had already been half sectioned so it was apparent that the depth of colour change associated with heating did not penetrate more than 5cm.



Figure 5.22: AM70, context 112, at Castlehill viewed from west (scale 0.15m) showing the sample locations.

The results (table 5.9) indicate that for AM70, all samples had a measureable remanence but the magnetisation was weak, so either does not contain sufficient magnetic minerals to record a consistent magnetic direction or was not heated to an adequate temperature. Therefore these samples were unable to undergo bulk demagnetisation or produce and did not reliable archaeomagnetic direction (table 5.9 and figure 5.23) as the mean direction showed too much scatter.

Magnetisation	Mean Dec (°)	Mean Inc (°)	$\alpha_{95}$	N	Demagnetisation field (mT)	No. of discordant samples
NRM	310.1	73.4	26.5	14	-	-

Table 5.9: Summary of the mean NRM for AM70 from Castlehill. The magnetic directions showed too much scatter to identify a mean direction (data are at site co-ordinates).

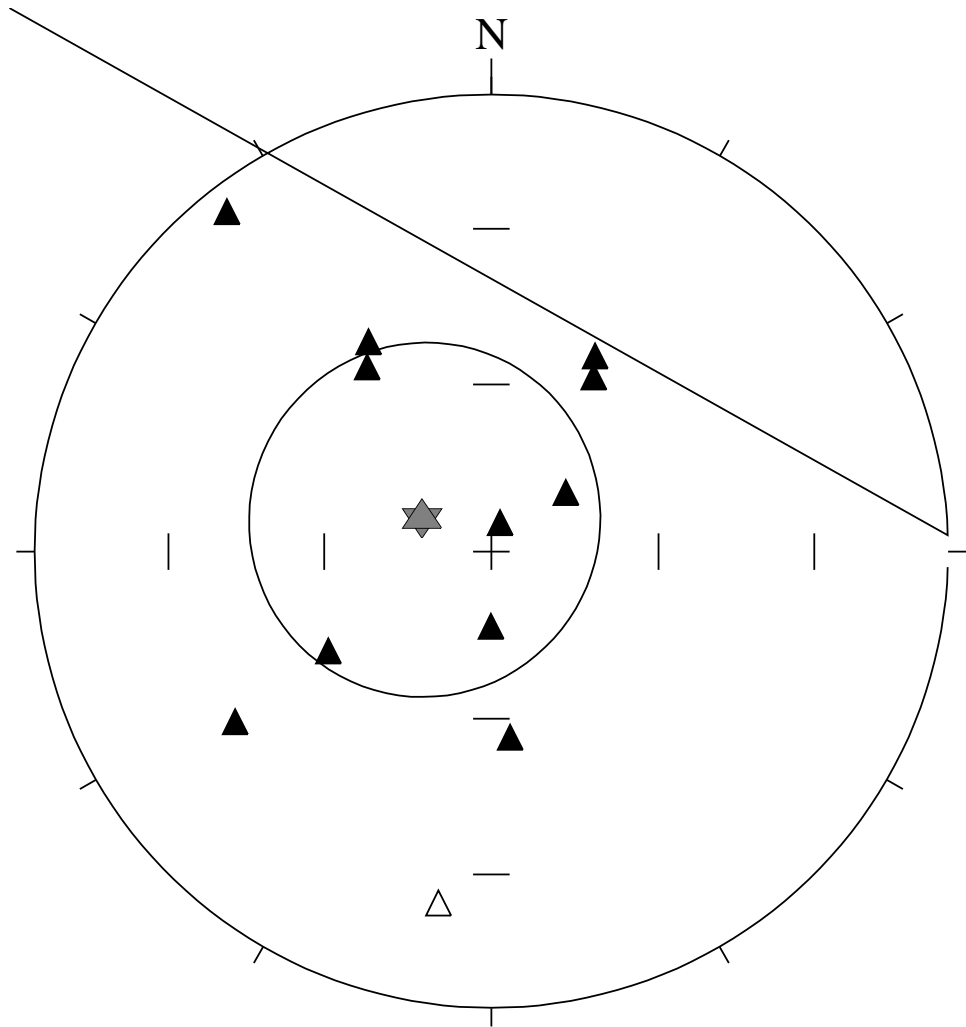


Figure 5.23: Stereoplot showing the NRM of AM70 from Castlehill. Closed (open) symbols represent positive (negative) inclinations. In the northern hemisphere inclinations should be positive, so any individual directions with negative inclinations are rejected. The mean direction is shown with the star and the  $\alpha_{95}$  value shown as a circle.

Trench 2 (AM71) also contained an area of paving and there was a strip of kerbing along the northern edge (figure 5.24). This arrangement suggested to the excavators the presence of a formal hearth structure. It appeared that this paving was originally composed of two or three large stones that had fractured due to exposure to intensive or prolonged heating. Again, as it was not possible to sample the stone, fragments both central to the paved area and butting the kerbing were lifted to enable samples to be taken from the clayey sand matrix they were set into. Underneath the paving there was a quantity of charcoal, the matrix was a dark reddish colour and there was evidence of some disturbance due to root activity.

According to the site records the paving had been sealed by a charcoal deposit; two implications from this are: that this paving was used as a hearth in the past and that it has remained undisturbed since the last firing event.



*Figure 5.24: AM71, context 204, Castlehill viewed from north-west (scale 0.15m) showing the sampling locations.*

Despite the evidence for root penetration in context 204, AM71 provided a magnetic direction (table 5.10) but further analysis suggested that, although the directions were stable, they were scattered (figure 5.25 and table 5.11). Two samples were rejected because they had negative inclinations, but the remaining directions showed too much scatter to produce an archaeomagnetic date. However, organic material recovered from the same feature as AM71 (RCHMS 2009) in Trench 2 was radiocarbon dated (GU-17025 -  $2150 \pm 30$ BP, Hawkins, pers. comm. 2008), providing an independent assessment of age of 360-50 cal BC, or early-mid Iron Age in the Scottish chronology.

Magnetisation	Mean Dec (°)	Mean Inc (°)	$\alpha_{95}$	N	Demagnetisation field (mT)	No. of discordant samples
NRM	24.21	53.3	36.7	10	20	-
ChRM	337.1	68.9	16.8	8	-	2

Table 5.10: Summary of the mean NRM and ChRM for AM71 from Castlehill; data are at site co-ordinates.

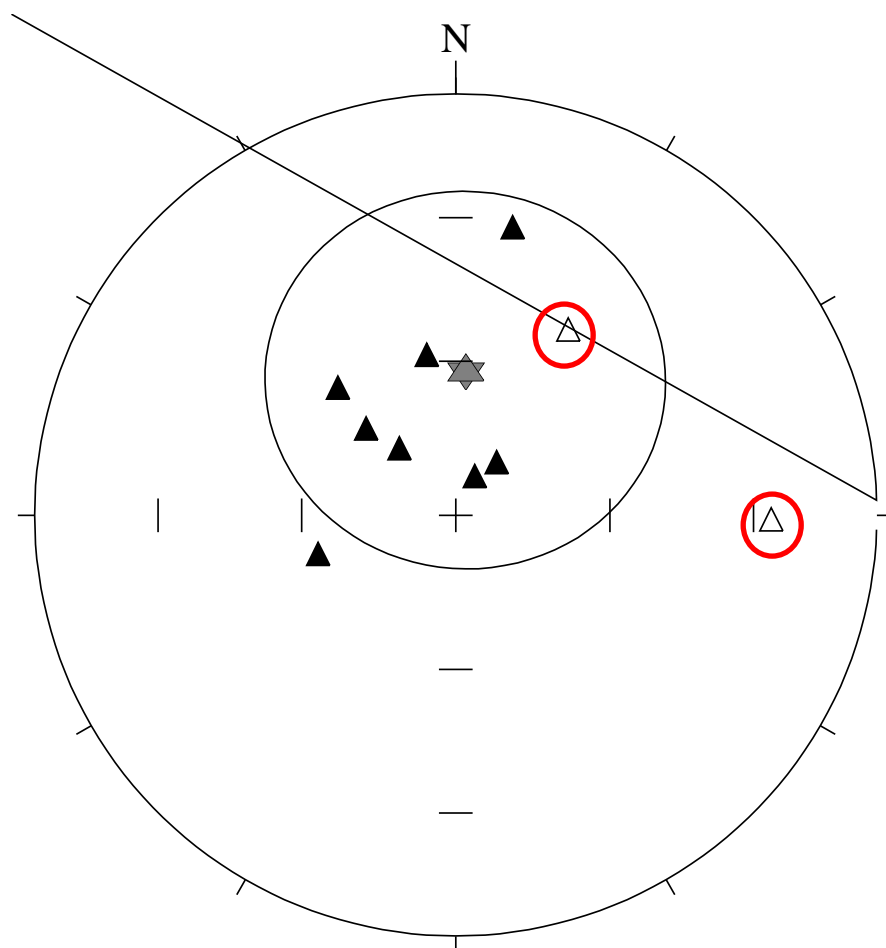


Figure 5.25: Stereoplot showing the ChRM of AM71 from Castlehill. Closed (open) symbols represent positive (negative) inclinations. In the northern hemisphere inclinations should be positive, so any individual directions with negative inclinations are rejected. The outliers that were removed are highlighted with red circles. The mean direction (including outliers) is shown by the grey star and the  $\alpha_{95}$  value shown as a circle.

Pilot sample reference	Reason for selecting	MDF	SI	% intensity remaining at 100mT
AM71/8	Representative, higher intensity	15	4, stable	6
AM71/10	Potential outlier, higher intensity	22	4, stable	3

*Table 5.11: The results from the pilot demagnetisation of samples from context 204 at Castlehill to investigate the nature of the magnetic signal.*

### 5.3.4 Kidlandlee: AM131

The site is located near to the village of Alwinton, Northumberland (NT912125), within the Northumberland National Park (figure 5.1 on page 140). It was part of a project to investigate the Bronze Age landscape of Northumberland. The aim was to understand later prehistoric use of upland landscapes and this area appears to have been used intensively with evidence for Bronze Age burial cairns, house platforms, field systems, palisade enclosures, cultivation plots and cross ridge dykes (Mason & Pope 2009). The structure under excavation was dated to the mid Bronze Age, on the basis of other archaeology in the area, but no diagnostic features or artefacts had been uncovered at the time of sampling. Only one feature was chosen for sampling, based on its state of preservation and evidence of firing. It was central to a roundhouse constructed with posts and consisted of a circular depression which showed evidence of being heated in antiquity. The hearth was a depression filled with a charcoal-rich deposit and there were five stake holes arranged around the northern edge of the depression (figure 5.26). Under the charcoal layer was a pale orange/red layer that was probably the clay lining for a pit hearth. The clay lining was not very thick; the deepest area was 4cm around the northern edge, close to the stake holes. Elsewhere the clay lining was only 1cm deep and was covering a very stony deposit underneath. Running along the SE edge and up the NW side of the feature there was evidence for animal burrows; these areas were avoided as much as possible, due to the possibility of disturbance of the hearth material (figure 5.26). This combination of factors severely reduced the area suitable for sampling.



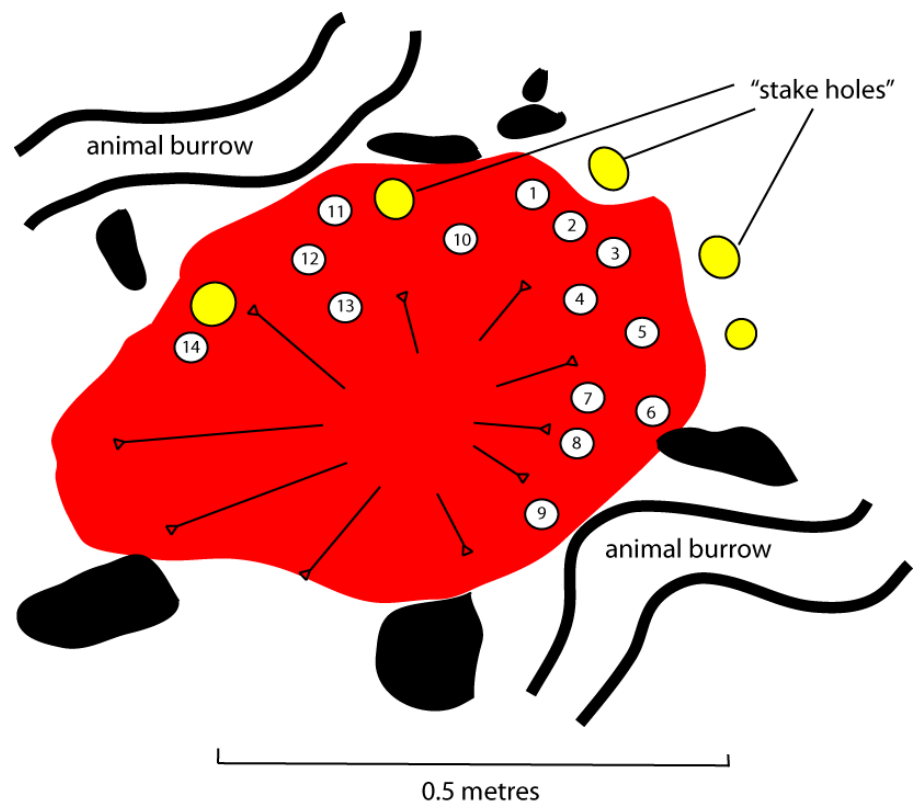


Figure 5.26: AM131, context 200, from Kidlandlee top photo viewed from the south (scale 0.5m). (Photograph © Rachel Pope, University of Liverpool); below is a schematic showing the sample locations. Sample numbers 6 and 9 were found to be outliers and from this plan the reason is probably due to their proximity to an animal burrow.

A total of 14 samples were collected and all of the samples had a measureable remanence, which indicates that the material sampled contained sufficient magnetic minerals to record a stable magnetic direction. Therefore these samples should be able to produce a reliable archaeomagnetic direction, although there were concerns regarding post-firing disturbance due to animal burrowing activity in the immediate vicinity of the hearth feature. Analysis of the magnetic data (table 5.12 and figure 5.27) and subsequent analysis (table 5.13) determined that 12 of the samples recorded a consistent magnetic direction. One sample (AM131/9) had a negative inclination and one sample was found to be discordant (AM131/6). Preliminary consideration of the finds recovered from the same phase of activity as the hearth sampled for AM131 suggests that this occupation dated to the Middle Bronze Age (Mason & Pope 2009), providing an independent assessment of age for this magnetic direction.

<b>Magnetisation</b>	<b>Mean Dec (°)</b>	<b>Mean Inc (°)</b>	<b><math>\alpha_{95}</math></b>	<b>N</b>	<b>Demagnetisation field (mT)</b>	<b>No. of discordant samples</b>
NRM	4.75	66.3	14.0	14	15	-
ChRM	2.2	63.6	5.3	12	-	2

*Table 5.12: Summary of the mean NRM and ChRM for AM131 from Kidlandlee, data are at site co-ordinates.*



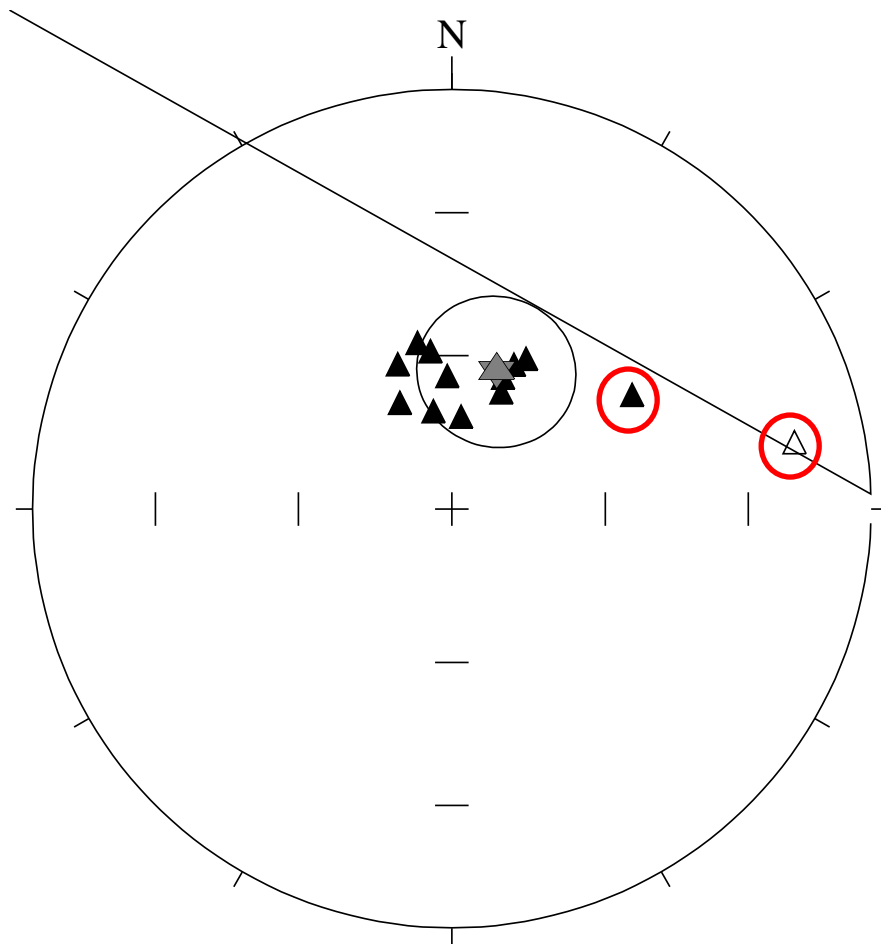


Figure 5.27: Stereoplot showing the ChRM of AM131 from Kidlandlee. Closed (open) symbols represent positive (negative) inclinations. In the northern hemisphere inclinations should be positive, so any individual directions with negative inclinations are rejected. The outliers that were removed are highlighted with red circles. The mean direction (including outliers) is shown by the grey star and the  $\alpha_{95}$  value shown as a circle.

Pilot sample reference	Reason for selecting	MDF (mT)	SI	% intensity remaining at 100mT
AM131/2	Representative, lower intensity	18	1, poorly stable	16
AM131/4	Representative, higher intensity	32.5	3, stable	15
AM131/6	Potential outlier, lower intensity	18	0.4, unstable	30

Table 5.13: The results from the pilot demagnetisation of samples from Kidlandlee to investigate the nature of the magnetic signal.

### 5.3.5 Market Deeping: AM173 and AM174

Permisson Homes were granted planning permission for the development of 5.3 hectares of arable farmland to the east of Godsey's Lane, Market Deeping (TF140104) in November 2009 (figure 5.1 on page 140). Since January 2010, Archaeological Project Services have been overseeing the stripping and ground works in advance of the proposed housing development and evidence for a potentially prehistoric rural settlement has been uncovered, leading to field excavation (Site MDGL10). Two features showed evidence of heating in antiquity, a fire pit (AM173) and a hearth (AM174) and both were selected for sampling (figures 5.28 and 5.29).



*Figure 5.28: AM173, context 704, at Market Deeping viewed from the south, scale 0.15m.*

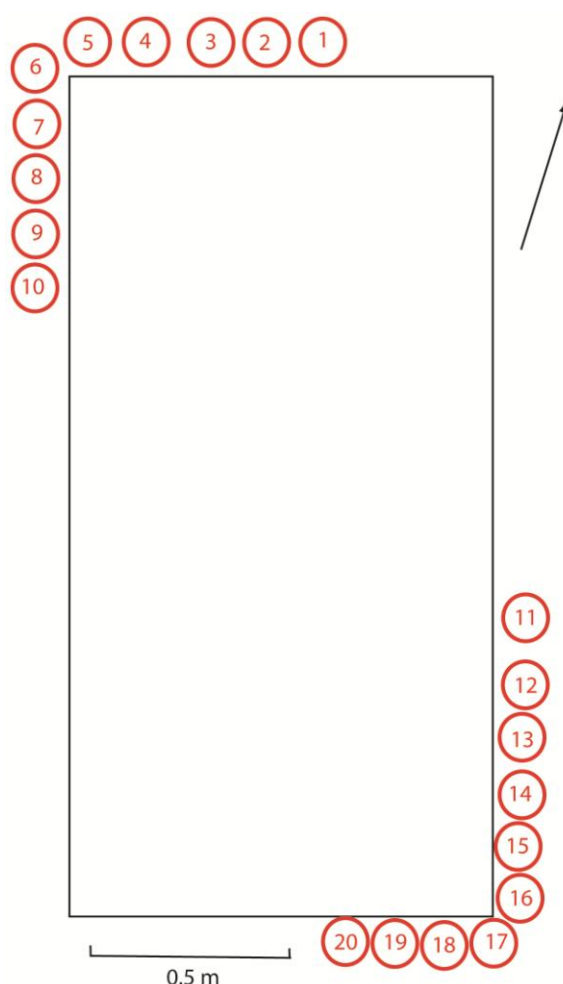


*Figure 5.29: AM174, contexts 1332 and 1333, at Market Deeping viewed from the west, scale 0.15m.*

AM173 was one of the first features to be revealed and had been exposed for four months, when the access road to the site had been inserted. It was a rectangular pit, 1m by 2m, but the northern edge was slightly arched. The long axis of this feature was orientated roughly north to south and had been dug into the natural soil, which was brownish-yellow clay (Munsell reference 10YR 6/6). The bottom was lined with a mixture of angular stones (10-20cm in size) and charcoal-rich silt; this fill also contained several sherds of ceramics typical of the Iron Age period in this region. Although the stones showed no evidence of heating, the edge of the pit was reddened which indicated that it may have been heated. This reddening (Munsell reference 2.5YR 4/6) was not consistent around the full circuit, but was concentrated in an arc around the northern edge and also in two parallel areas towards the southern end. The central sections of the long axis and the southern edge showed no signs of heating. Where there was reddening, it only radiated 3 to 4 cm away from the edge of the pit wall and appeared to penetrate to a depth of 9-10 cm, leaving the bottom 4 cm unaffected. The area around the pit



showed some signs of cracking, due to drying, as it had been exposed since January. A total of 20 samples were collected along the north-west and south-east corners of the pit (figures 5.28 and 5.30) and all of the samples had a measureable magnetic remanence, which indicates that the material sampled contained sufficient magnetic minerals to record a stable magnetic direction. Therefore these samples could potentially produce a reliable archaeomagnetic date, although there were concerns regarding the strength of the magnetic signal and the amount of cracking visible in the walls. Analysis of the magnetic data (table 5.14 and figure 5.31) and further analysis (table 5.15) determined that 19 of the samples recorded a magnetic direction, but the magnetic signal was only poorly stable. One sample (AM173/8) was found to be discordant.



*Figure 5.30: Schematic plan of the fire pit at Market Deeping showing the locations of sample AM173.*

Magnetisation	Mean Dec (°)	Mean Inc (°)	$\alpha_{95}$	N	Demagnetisation field (mT)	No. of discordant samples
NRM	348.5	73.0	10.2	20	5	-
ChRM	351.2	72.7	5.8	19	-	1

Table 5.14: Summary of the mean NRM and ChRM for AM173 from Market Deeping, data are at site co-ordinates.

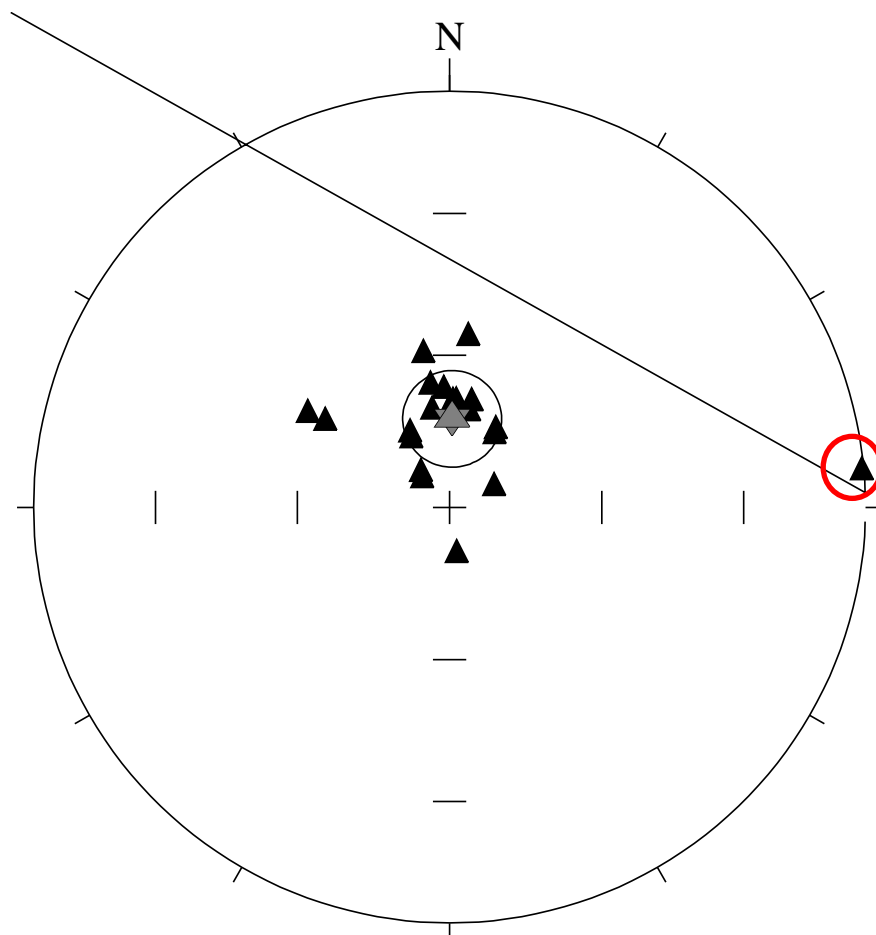


Figure 5.31: Stereoplot showing the ChRM of AM173 from Market Deeping. Closed (open) symbols represent positive (negative) inclinations. In the northern hemisphere inclinations should be positive, so any individual directions with negative inclinations are rejected. The outlier that was removed is highlighted with a red circle. The mean direction (including outliers) is shown by the grey star and the  $\alpha_{95}$  value shown as a circle.

Pilot sample reference	Reason for selecting	MDF (mT)	SI	% intensity remaining at 100mT
AM173/3	Representative/high intensity	10	1.9, poorly stable	2
AM173/8	Potential outlier/high intensity	15	0.6, meta-stable	1
AM173/12	Representative/mid intensity	10	1.0, poorly stable	11
AM173/15	Potential outlier/low intensity	10	0.5, meta-stable	17
AM173/17	Representative/mid intensity	12	2.2, poorly stable	4

*Table 5.15: The results from the pilot demagnetisation of samples from the fire pit at Market Deeping to investigate the nature of the magnetic signal.*

AM174 was a hearth in area B, where there appeared to be some concentration of prehistoric activity. This hearth was a 60 x 90cm oval-shaped feature and formed a shallow depression of dark reddish brown material (context 1333 Munsell reference 10R 3/4), which appeared to have been lined with a strong brown clay (context 1332 Munsell reference 7.5YR 4/6), (figure 5.29). The clay lining was patchy and showed extensive signs of cracking, but was only 1 cm deep. It appeared that heat had penetrated into the context below, 1333, and had affected this material to a depth of at least 3cm. This feature had only been revealed the week before the site visit and had remained covered with plastic sheeting. A total of 20 samples were collected, 10 samples from each context (1332 and 1333; figure 5.32). All of the samples had a measureable magnetic remanence, which indicates that the material sampled contained sufficient magnetic minerals to record a stable magnetic direction, which suggests that these samples could potentially produce a reliable archaeomagnetic age; however, there was a systematic difference observed between the intensities of the materials of the clay lining, context 1332, and the base of the hearth, context 1333. With the lining displaying intensities ten times higher than the base, the average intensity for context 1332 was  $540 \times 10^{-6} \text{ Am}^2$ , but for context 1333 was  $25 \times 10^{-6} \text{ Am}^2$ . Analysis of the magnetic data (table 5.16 and figure 5.33) determined that 18 of the samples recorded a magnetic direction and

that the magnetic signal was stable (table 5.17). Two samples were discordant (AM174/4 and AM174/6).

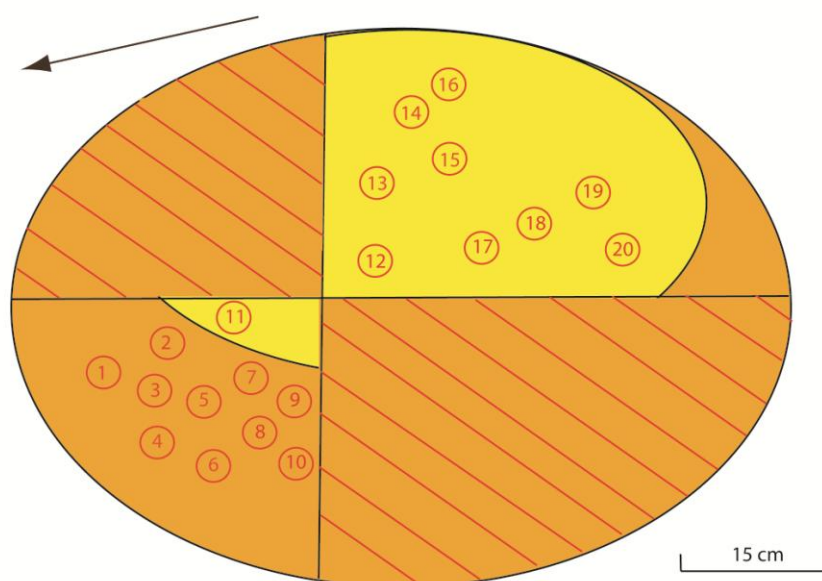


Figure 5.32: Schematic plan of the hearth at Market Deeping showing the location of the samples AM174: where context 1331 is orange with red stripes, c/ontext 1332 is yellow, context 1333 is orange (also see figure 5.29).

Magnetisation	Mean Dec (°)	Mean Inc (°)	$\alpha_{95}$	N	Demagnetisation field (mT)	No. of discordant samples
NRM	334.5	66.1	8.0	20	7.5	-
ChRM	343.0	64.4	4.5	18	-	2

Table 5.16: Summary of the mean NRM and ChRM for AM174 from Market Deeping, data are at site co-ordinates.

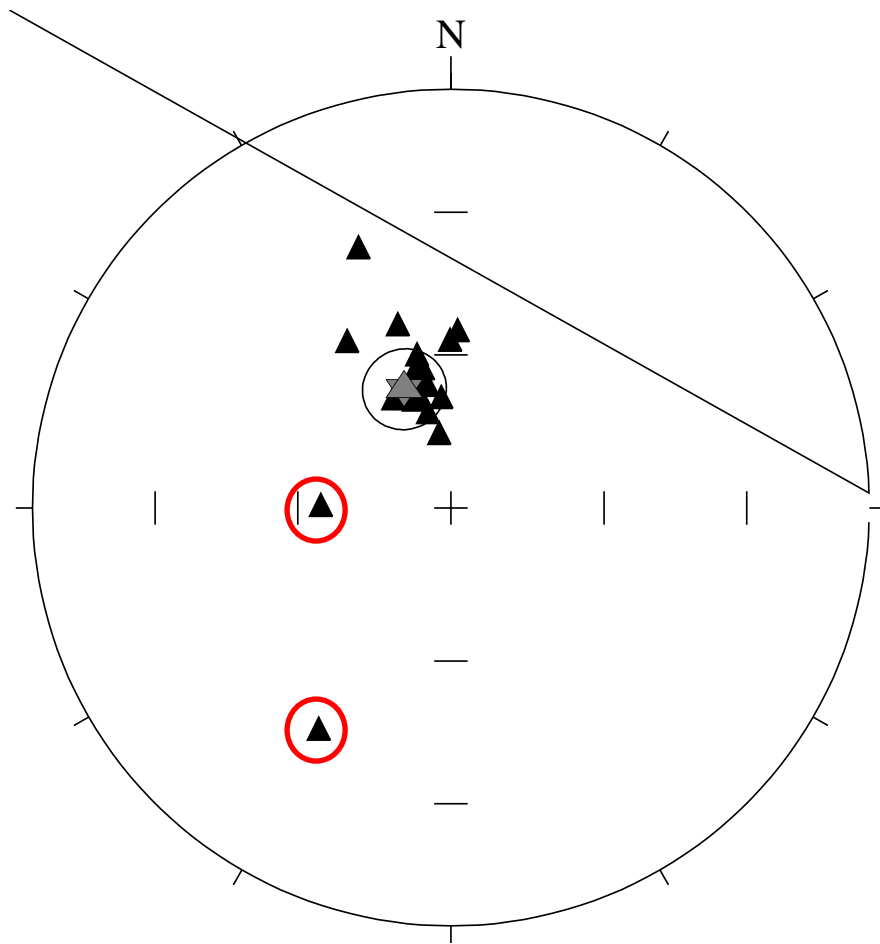


Figure 5.33: Stereoplot showing the ChRM of AM174 from Market Deeping. Closed (open) symbols represent positive (negative) inclinations. In the northern hemisphere inclinations should be positive, so any individual directions with negative inclinations are rejected. The outliers that were removed are highlighted with red circles. The mean direction (including outliers) is shown by the grey star and the  $\alpha_{95}$  value shown as a circle.

Pilot sample reference	Reason for selecting	MDF (mT)	SI	% intensity remaining at 100mT
AM174/4	Potential outlier/low intensity	12.5	0.6, meta-stable	3
AM174/6	Representative/low intensity	15	0.7, meta-stable	1
AM174/14	Potential outlier/mid intensity	15	7.5, very stable	18
AM174/16	Representative/high intensity	15	4.5, stable	5
AM174/20	Representative/mid intensity	15	4.0, stable	3

Table 5.17: The results from the pilot demagnetisation of the hearth at Market Deeping to investigate the nature of the magnetic signal.



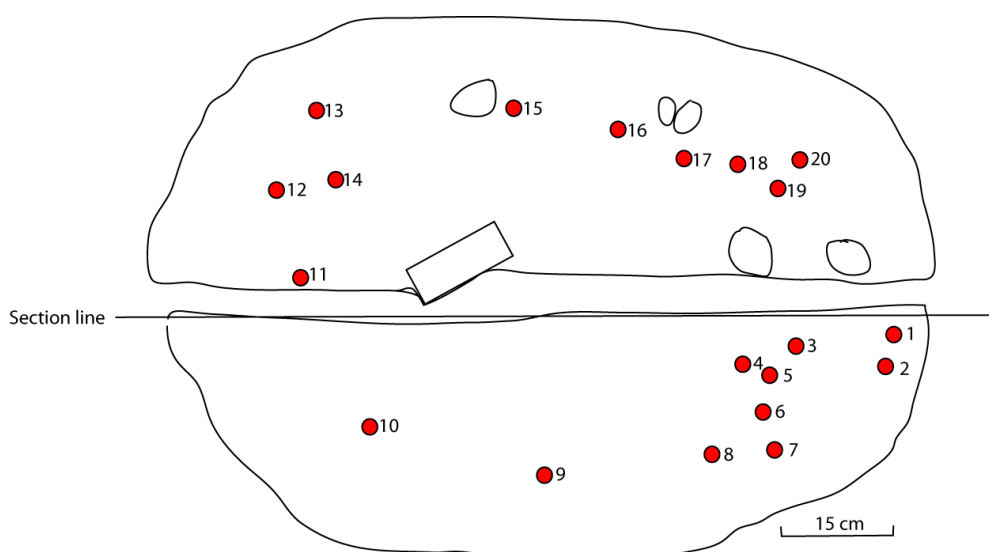
### 5.3.6 Mellor: AM134

The site of Mellor is located east of Stockport in Greater Manchester (SJ984886; figure 5.1 on page 140). It was discovered in 1995, when the residents of the Old Vicarage noticed crop marks in their garden. This observation prompted them to set up the Mellor Archaeological Trust and, with help from the University of Manchester, they began to excavate. These crop marks proved to be the ditch of a potential Iron Age hill top settlement, with several roundhouses surrounded by a deep inner ditch and shallower boundary ditch. The roundhouse structures were dated to the Iron Age on the basis of associated finds, including iron working slag, briquetage and crucible fragments (Peter Noble, pers. comm. 2008). This site has produced some of the first examples of Iron Age pottery from northwest England. The stratigraphy of the structures is complex and currently unresolved but a ring of post-holes, approximately 15m in diameter and surrounded by a possible drip gully, contained an oval of reddened material in the centre. This feature was interpreted as a central hearth (figure 5.34), and was selected for sampling based on the evidence of firing.



*Figure 5.34: AM134, context 224, at Mellor viewed from north (scale 0.15m).*

The oval of reddened material sampled, context 224, was 1.1 metres along the longest axis (figure 5.35). Context 224 was a clay sand matrix with approximately 20% clay and displayed a distinct colour change to the surrounding material. Context 224 was moist and weak, with approximately 15% inclusions of <5cm rounded stones and some patches of black material, possibly charcoal, included in the matrix. Before visiting the site, excavation had commenced to half section this feature. It is possible that workers kneeling on the context in order to work could have displaced some of the material. A total of 20 samples were collected and all of the samples had a measureable magnetic remanence, which indicates that the material sampled contained sufficient magnetic minerals to record a stable magnetic direction, which suggests that these samples could potentially produce a reliable archaeomagnetic date, although there were concerns regarding the strength of the magnetic signal. Analysis of the magnetic data (table 5.18 and figure 5.36) and further analysis (table 5.19) determined that 18 of the samples recorded a magnetic direction but that the magnetic signal was only poorly stable. Two samples did not undergo bulk demagnetisation (AM134/11 and AM134/20), because their NRM displayed very weak intensities and negative inclinations; no other samples were found to be discordant.



*Figure 5.35: A schematic of AM134 showing the location of the samples collected from Mellor.*

Magnetisation	Mean Dec (°)	Mean Inc (°)	$\alpha_{95}$	N	Demagnetisation field (mT)	No. of discordant samples
NRM	5.7	68.3	16.4	20	7.5	-
ChRM	358.6	65.8	9.9	18	-	2

Table 5.18: Summary of the mean NRM and ChRM for AM134 from Mellor, data are at site co-ordinates.

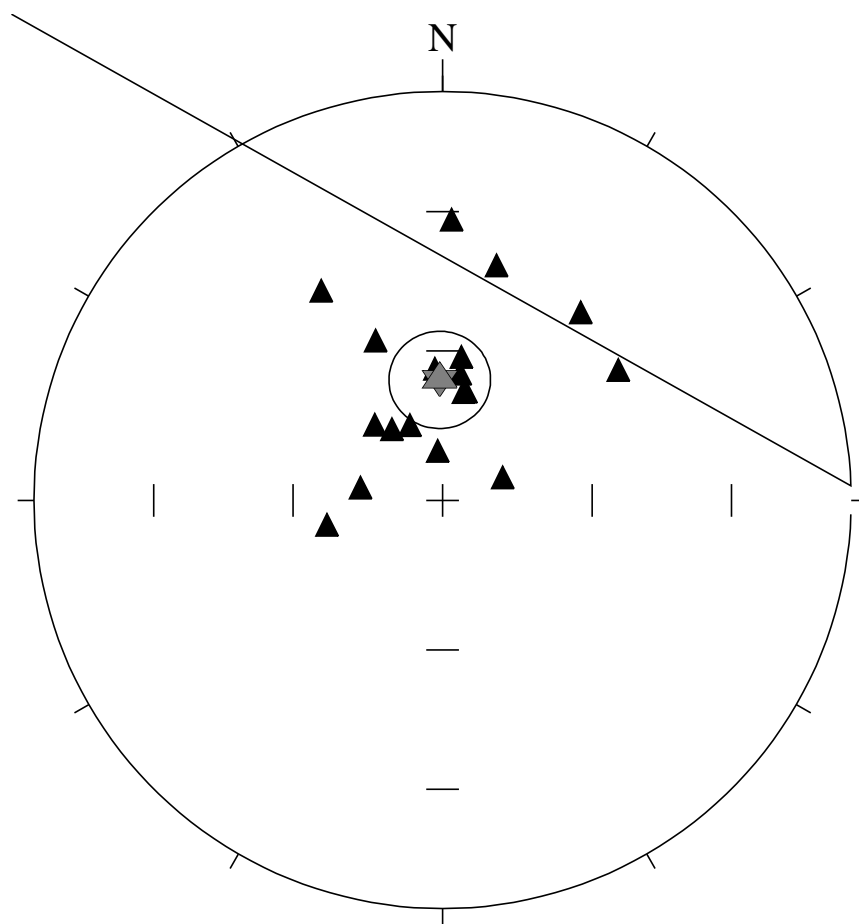


Figure 5.36: Stereoplot showing the ChRM of AM134 from Mellor. Closed (open) symbols represent positive (negative) inclinations. In the northern hemisphere inclinations should be positive, so any individual directions with negative inclinations are rejected. The mean direction is shown by the grey star and the  $\alpha_{95}$  value shown as a circle.

Pilot sample reference	Reason for selecting	MDF (mT)	SI	% intensity remaining at 100mT
AM134/3	Representative, low intensity	20	2, poorly stable	20
AM134/4	Representative, higher intensity	17.5	2, poorly stable	10
AM134/10	Potential outlier	20	0.6, meta-stable	30
AM134/14	Potential outlier	28	2, poorly stable	11

*Table 5.19: The results from the pilot demagnetisation of samples from Mellor to investigate the nature of the magnetic signal.*

After sampling, further excavations revealed quantities of an unknown typology of prehistoric ceramic from the drip gullies of several of the roundhouses. Soil samples from these gullies were collected and it proved possible to obtain radiocarbon dates which all provide a date range of 370-160 cal BC or mid Iron Age (Noble 2010). One of the soil samples (SUERC-24543 (GU-19183)) was collected from the drip gully associated with the hearth sampled for archaeomagnetic dating, which enables this magnetic direction to be included in the revised database.

### **5.3.7 Poulton-le-Fylde: AM84, AM85 and AM86**

Wyre Estuary Poulton, just on the outskirts of Poulton-le-Fylde (SD364411), had been stripped as part of the landscape preparations for a housing development (figure 5.1 on page 140). Two circular structures had been revealed and were interpreted as Iron Age roundhouses. Structure 226 was undergoing excavation at the time of sample collection and it was cut by several field drains and medieval ridge and furrow, the latter is indicative of long-term land use in this locality. The structures were dated to the first millennium B.C. on the basis of the architecture present as negative features, i.e. pits or post holes, and the pottery recovered including black burnished ware and red coarseware. A total of three areas of possible burning were sampled and these were uncovered in close proximity to each other within the confines of the structure. One area of burning was in the northern segment of the structure, whereas the other two were in the south-west

quadrant and in close proximity to each other. At the time of sampling the features had only just been cleaned back and initial recording completed, so samples were only taken from the exposed surfaces of each context. A total of twenty samples were taken from each of three contexts within structure 226, contexts: 213, 224 and 300, as it was believed by the excavators to show evidence of heating.

***Structure 226, AM84, context 213***

This context was in the northern segment of the structure and was approximately 3 m by 1.3 m. This context formed an elongated oval, which contained what appeared to be two post holes, cuts 221 and 223. When the samples were taken the relationship between the post holes and context 213 was unclear; however, the western half of the context was disturbed by a modern field drain. The material sampled was a deep reddish-orange colour and mostly clay with some silt present. Sampling focused on the northern section of the context as this area had no inclusions and showed little disturbance from either the field drain or the post holes (figure 5.37).



*Figure 5.37: AM84, context 213, at Poulton-le- Fylde viewed from north-east (scale 1m) showing the sample locations.*

All of the samples from context 213 (AM84 - table 5.20 and figure 5.38) were weakly magnetised and displayed considerable scatter in the recorded magnetic direction. Given the poor quality of the data displayed by the samples it was decided not to re-measure with a more sensitive cryogenic magnetometer, such as a superconducting quantum interface device (SQUID), due to the additional expense this would incur and it was felt that it would not yield any further information. These results are taken to indicate that the material had neither been heated *in situ* to a sufficient temperature, nor contains a suitable mineralogy to retain a magnetic signal within its matrix. Given the archaeological evidence, it is unlikely that the reddening of the material was due to a past heating event making the features undateable by archaeomagnetic dating.

<b>Magnetisation</b>	<b>Mean Dec (°)</b>	<b>Mean Inc (°)</b>	<b><math>\alpha_{95}</math></b>	<b>N</b>	<b>Demagnetisation field (mT)</b>	<b>No. of discordant samples</b>
NRM	310.3	63.1	24.3	16	-	-

*Table 5.20: Summary of the mean NRM for AM84 from Poulton-le-Fylde; the magnetic directions showed too much scatter to identify a reliable mean direction for archaeomagnetic dating purposes, data are at site co-ordinates.*

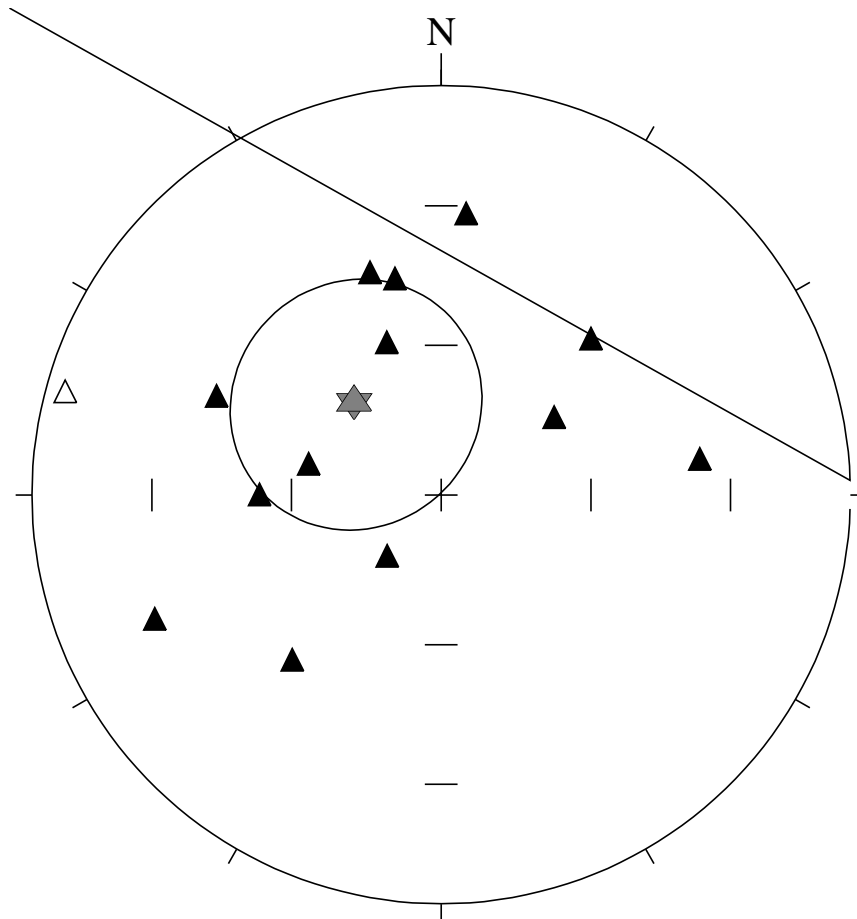
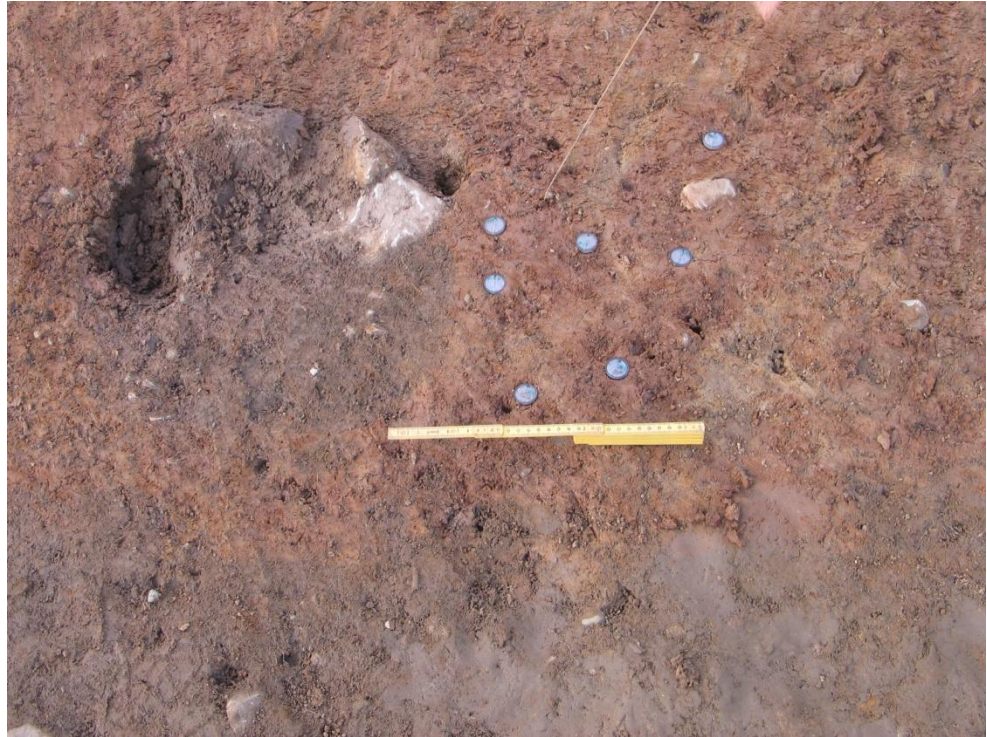


Figure 5.38: Stereoplot showing the NRM of AM84 from Poulton-le-Fylde. Closed (open) symbols represent positive (negative) inclinations. In the northern hemisphere inclinations should be positive, so any individual directions with negative inclinations are rejected. The mean direction of the data plotted is shown by the grey star and the  $\alpha_{95}$  value shown as a circle.

#### **Structure 226, AM85, context 224**

In the south-west segment of the structure there were two further areas of reddening, again associated with post holes (context 224 and 300). Context 224 is the furthest south of these two and had been truncated by later features; on the south side by a medieval furrow and on the east side by a possible ditch with sandy fill. This context was predominately dark-orange clay and only a 1.3m by 1.3m area remains, with some mottling around the post hole (cut 208). There were some angular inclusions around the extremities, particularly to the west of the feature, so these areas were avoided during sampling (figure 5.39).





*Figure 5.39: AM85, context 224, at Poulton-le-Fylde viewed from south (scale 0.3m) showing the sample locations.*

A total of twenty samples were taken from context 224 (AM85 – table 5.21 and figure 5.40). All of the samples were weakly magnetised and displayed considerable scatter in the recorded magnetic direction; these findings are the same as those from AM84.

<b>Magnetisation</b>	<b>Mean Dec (°)</b>	<b>Mean Inc (°)</b>	<b><math>\alpha_{95}</math></b>	<b>N</b>	<b>Demagnetisation field (mT)</b>	<b>No. of discordant samples</b>
NRM	3.1	63.4	28.1	7	-	-

*Table 5.21: Summary of the mean NRM for AM85 from Poulton-le-Fylde; the magnetic directions showed too much scatter to identify a reliable mean direction for archaeomagnetic dating purposes, data are at site co-ordinates.*



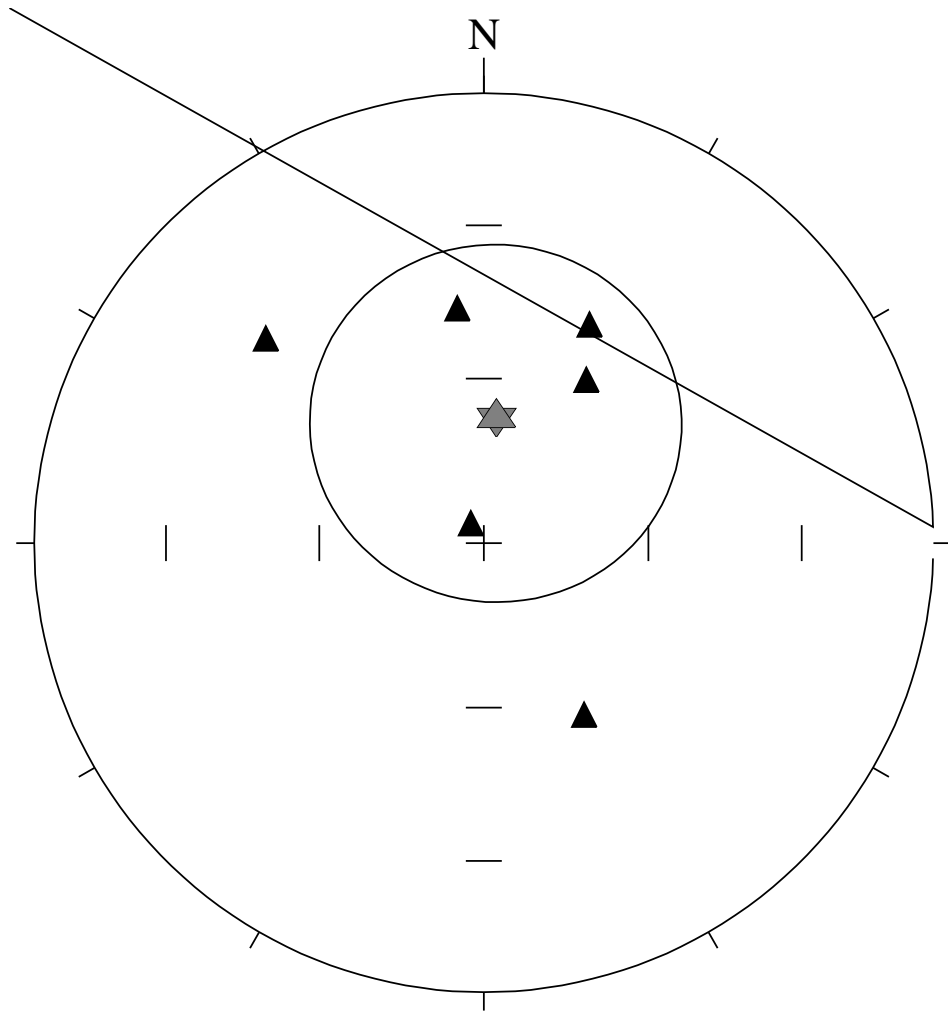


Figure 5.40: Stereoplot showing the NRM of AM85 from Poulton-le-Flyde. Closed (open) symbols represent positive (negative) inclinations. In the northern hemisphere inclinations should be positive, so any individual directions with negative inclinations are rejected. The mean direction for the data plotted is shown by the grey star and the  $\alpha_{95}$  value shown as a circle.

#### **Structure 226, AM86, context 300**

This isolated patch of reddened material was only 0.5m further north of context 224. This context was approximately 1m by 1.4m and was roughly circular and consisted of orange/red, clay with some small rounded pebbles and lumps of charcoal. Along the western edge of the deposit there was evidence for another post-hole, or possibly part of the drip gully that defined the edge of the structure (figure 5.41).



Figure 5.41: AM86, context 300, at Poulton-le-Fylde viewed from south (scale 0.3m) showing the sample locations.

A total of twenty samples were taken from context 300 (AM86 – table 5.22 and figure 5.42). All of the samples were weakly magnetised and displayed considerable scatter in the recorded magnetic direction, findings are the same as for AM84.

Magnetisation	Mean Dec (°)	Mean Inc (°)	$\alpha_{95}$	N	Demagnetisation field (mT)	No. of discordant samples
NRM	32.1	80.1	16.7	7	-	-

Table 5.22: Summary of the mean NRM for AM86 from Poulton-le-Fylde, the magnetic directions showed too much scatter to identify a reliable mean direction for archaeomagnetic dating purposes, data are at site co-ordinates.

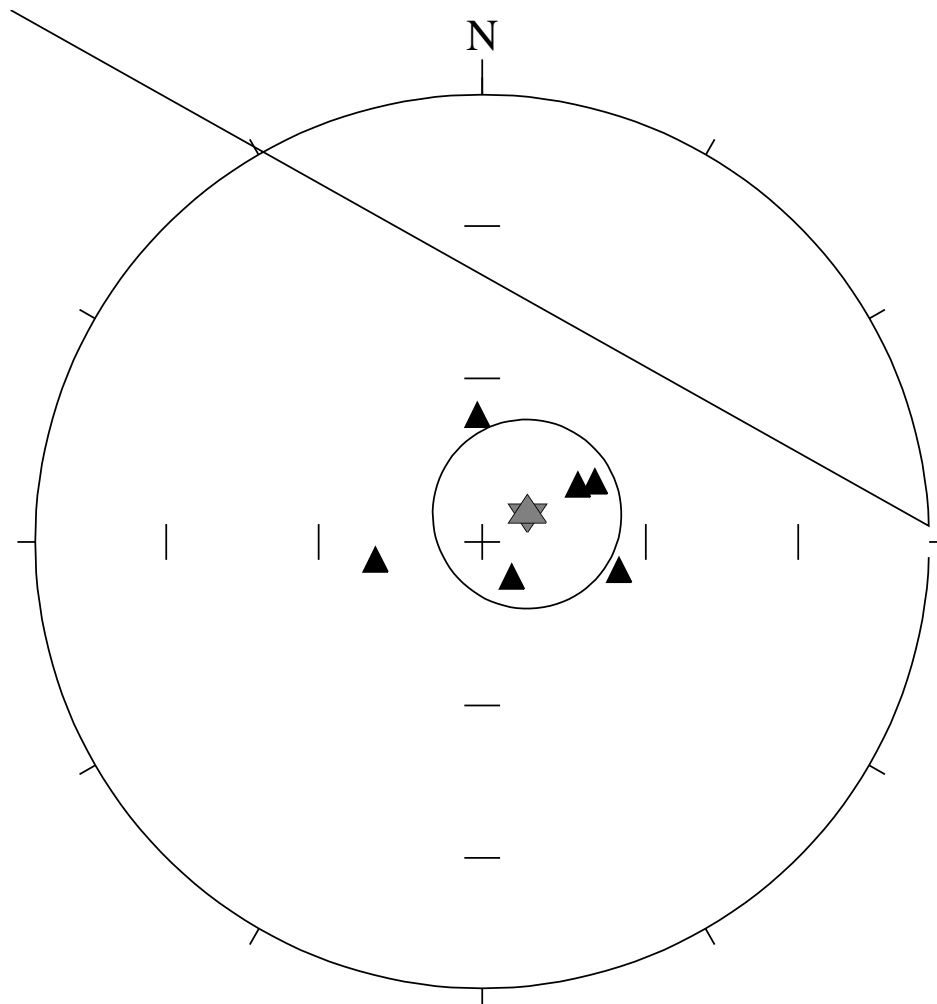


Figure 5.42: Stereoplot showing the NRM of AM86 from Poulton-le-Fylde. Closed (open) symbols represent positive (negative) inclinations. In the northern hemisphere inclinations should be positive, so any individual directions with negative inclinations are rejected. The mean direction of the data plotted is shown by the grey star and the  $\alpha_{95}$  value shown as a circle.

### 5.3.8 Sadlers End: AM180

The site of Sadlers End (SU780703), site code SES 0587 (figure 5.1 on page 140), contained evidence for prolonged use with at least two Bronze Age cremations and a series of small “figure of eight” iron smelting features, identified during excavations within an area of land recently purchased by Wokingham Cricket Club. Context 263 was chosen for sampling based on its state of preservation, the evidence for firing in antiquity and that it was the largest and most substantial furnace uncovered. The feature was roughly circular and 1 m in diameter; the entrance was on the western edge of the circuit, to make use of the natural slope

by allowing the molten content to flow downhill when the furnace was in use (figure 5.43). The western edge of the feature, particularly the southern part of the entrance, showed signs of collapse in antiquity. It is presumed that this collapse would have been related to breaking the wall to release the slag, because the entire area south-west and downslope of the furnace was covered with a substantial layer of burnt material (Jamie Lewis, pers. comm. 2010). At the time of sample collection over 2000kg of slag had been recovered from this area. In addition, several substantial pieces of Iron Age decorated ceramics had also been recovered from within this burnt layer. The entire structure appears to have been constructed by digging a circular depression into the natural bedrock, which was lined with clay. The floor of the furnace was then lined with burnt flints; the reasons for these are unclear but they were still *in situ*. The furnace walls showed evidence of being heated and ranged from a reddish-brown (Munsell reference 5YR 5/3) to reddish-yellow (Munsell reference 7.5YR 6/6) colour. The wall varied in thickness around the circumference of these feature but was typically 12cm and the wall survived to a depth of 15-30cm. Finally, the wall at the south of the entrance, as well as showing signs of collapse, had also been penetrated by several roots, which is not conducive to this method of dating. An overview of the feature and sampling locations are provided by figure 5.44. The site had been visited by English Heritage, who had suggested that this feature was unsuitable for sampling as it was circular and would have been adversely affected by magnetic refraction. Therefore, the entire circuit of wall that survived *in situ* was sampled to look for any signs of magnetic refraction.



Figure 5.43: Furnace at Sadlers End, context 263, viewed from the north (scale 0.15m).

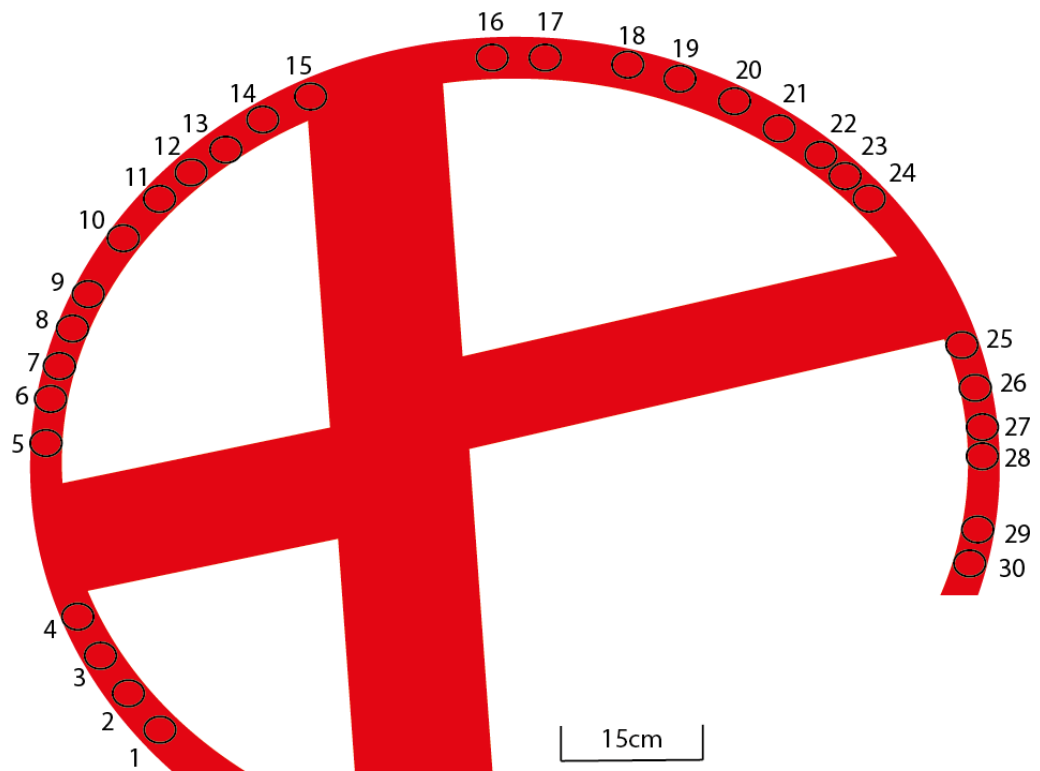


Figure 5.44: A schematic of AM180, context 263, at Sadlers End viewed from the west (scale 15cm) showing the location of the samples.

A total of thirty samples were taken from cleaned horizontal surfaces on the feature and these were collected using the button method, because the material was hard. For one sample, AM180/28, the plastic disc did not adhere so was excluded from the rest of the analyses. All of the remaining 29 samples had a measurable remanence (table 5.23), which indicates that the material sampled contained sufficient magnetic minerals to record a stable magnetic direction. Analysis of the magnetic data determined that 22 of the samples recorded a consistent and stable magnetic direction (figure 5.45 and table 5.24).

Magnetisation	Mean Dec (°)	Mean Inc (°)	$\alpha_{95}$	N	Demagnetisation field (mT)	No. of discordant samples
NRM	355.1	64.1	8.3	29	7.5	-
ChRM	354.7	65.6	5.0	22	-	7

*Table 5.23: Summary of the mean NRM and ChRM for AM180 from Sadlers End, data are at site co-ordinates.*

Pilot sample reference	Reason for selecting	MDF (mT)	SI	% intensity remaining at 100mT
AM180/8	Representative, high intensity	10	0.6, meta-stable	2
AM180/9	Representative, average intensity	15	1.6, poorly stable	6
AM180/12	Representative, high intensity	12.5	7.0, very stable	17
AM180/14	Representative, average intensity	12.5	5.5, very stable	16
AM180/19	Potential outlier, low intensity	40	1.5, poorly stable	50
AM180/21	Potential outlier, low intensity	15	0.8, meta-stable	18
AM180/23	Representative, average intensity	12.5	4.1, stable	19
AM180/29	Potential outlier, low intensity	18	1.2, poorly stable	19

*Table 5.24: The results from the pilot demagnetisation of Sadlers End samples to investigate the nature of the magnetic signal.*

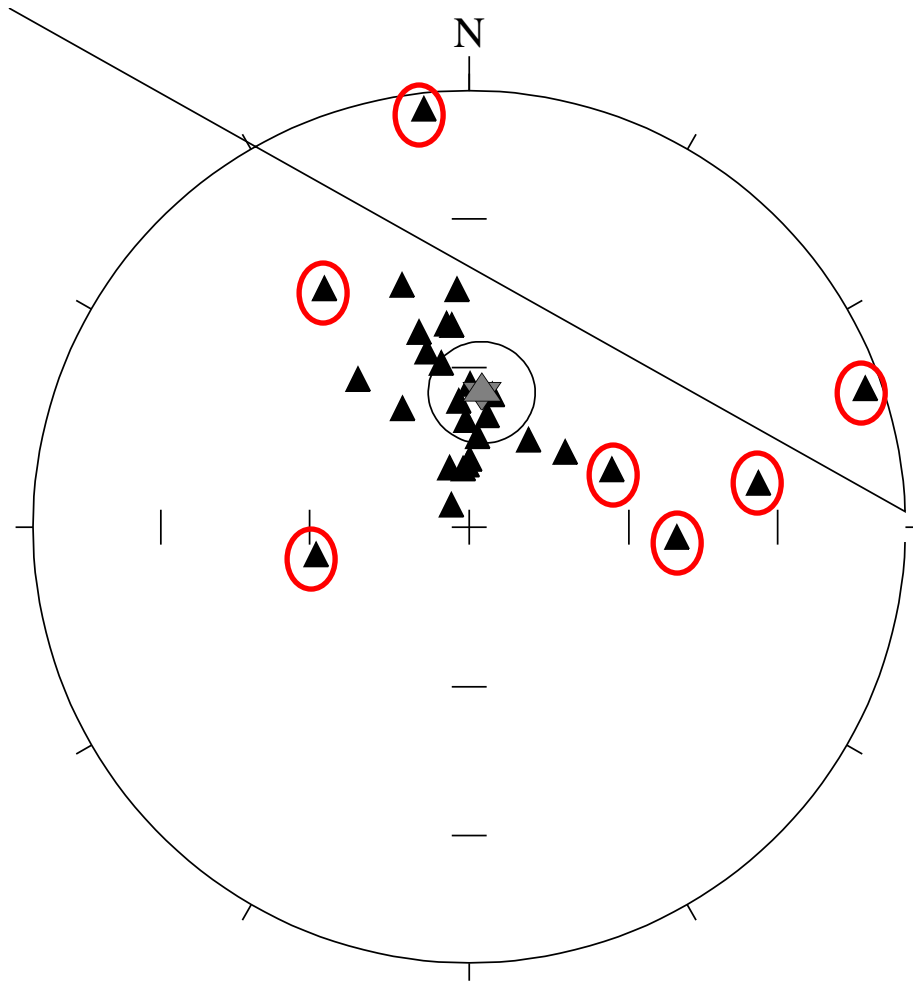


Figure 5.45: Stereoplot showing the ChRM of AM180 from Sadlers End. Closed (open) symbols represent positive (negative) inclinations. In the northern hemisphere inclinations should be positive, so any individual directions with negative inclinations are rejected. The outliers that were removed are highlighted with red circles. The mean direction (including outliers) is shown by the grey star and the  $\alpha_{95}$  value shown as a circle.

Observations made regarding the collapse along the western edge of the circuit were borne out by the shallow inclinations shown by samples AM180/29 and AM180/30, and so these were rejected. Further statistical analysis of the remaining 28 samples data revealed that four samples were statistical outliers. AM180/19 and AM180/21 deviated significantly from the rest of the samples, using the statistical procedures recommended by McFadden and McElhinny (2000: 92). Pilot demagnetisation had already highlighted that AM180/19 displayed atypical magnetic properties (table 5.24) and both samples displayed low intensities, below  $3 \times 10^{-6} \text{ Am}^2$ , which suggested that they were all unstable. During the site visit it was

mentioned that part of the northern section of the wall had been stood on. Plotting the remaining 20 samples on a stereoplot highlighted that the samples from the section of wall affected (AM180/4, AM180/6 and AM180/7) had indeed been disturbed, and all in the same way, as they plotted together away from the rest of the group so were excluded as outliers. There was no other obvious evidence to suggest that the magnetic directions from this feature had been adversely affected. However, the occurrence of a large  $\alpha_{95}$  does suggest a lot of scatter, which is consistent with previous observations (Tarling *et al.* 1986). It is unfortunate that, in this case, samples had to be rejected due to wall movement associated with human activity after the last heating event (figure 5.46). There is some evidence for the distortion of the magnetism across a fired feature following a sine curve observed by earlier workers (Harold 1960; Weaver 1962) and there does appear to be a trend where the declinations are more easterly, with steeper inclinations, on one half of the feature, with the opposite occurring on the other half of the feature. Closer examination of individual directions suggests that each appear to fall within the error values of the mean ChRM in at least one component. For example, with AM180/5 the declination falls outside the errors of the ChRM mean, but the inclination falls within the errors. From this observation it is only possible to recommend that when circular features are encountered it would appear to be particularly important that the entire circumference is sampled (Soffel & Schurr 1990). Due to the method of constructing this feature it is unlikely that this affect is due to “kiln wall fall out” (Harold 1960). The often cited “magnetic refraction” is typically given as the cause of this phenomenon, yet there is currently neither a satisfactory explanation nor convincing theory available for how magnetic refraction is generated or how it affects the remanence of the structure. It does serve illustrate the necessity to collect samples from across the entire structure as recommended in the English Heritage guidelines (Linford 2006).



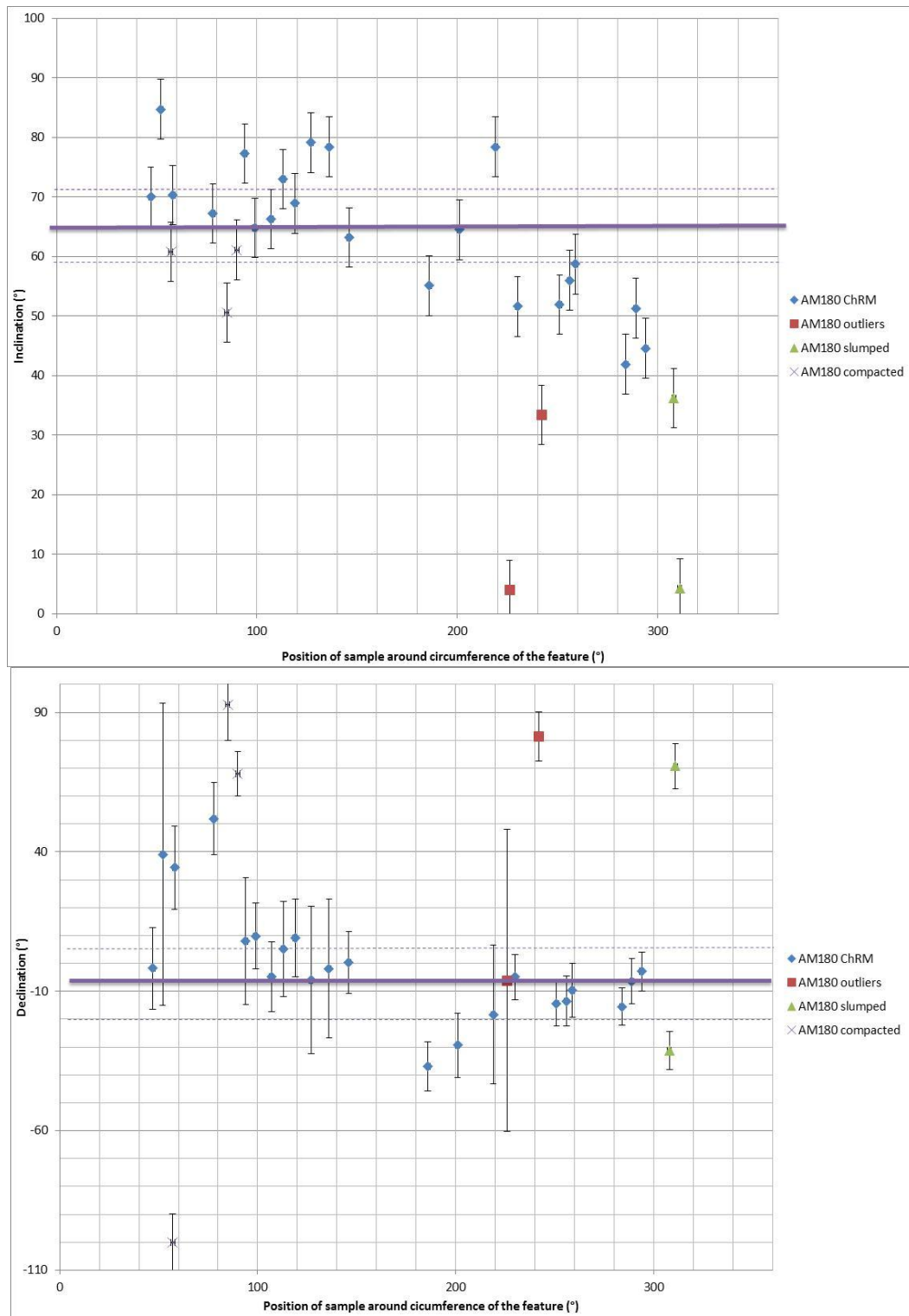


Figure 5.46: Graphs showing the ChRM from Sadlers En,d plotting inclination (top) and declination (bottom) against the azimuth to investigate the potential presence of magnetic refraction or any systematic distortion. Mean ChRM is shown as a purple line, with errors shown as dashed lines. This presentation of the data appears to show that directions from one half of the feature show more easterly declinations and steeper inclinations with the opposite for the other half of the feature.

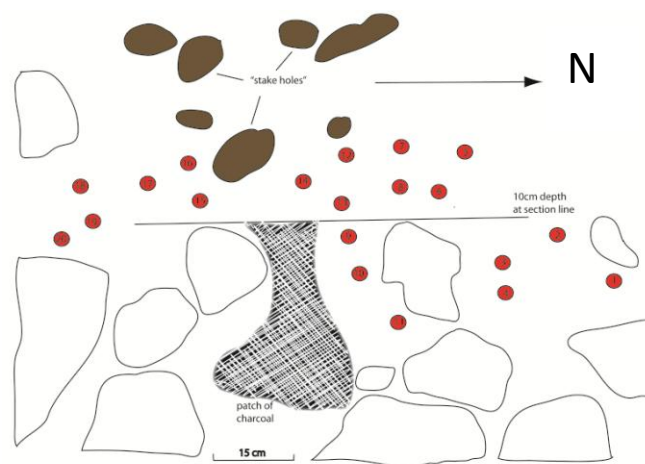
### 5.3.9 Street House: AM132 and AM133

The site is located near to the village of Loftus in North Yorkshire (NZ739197) (figure 5.1 on page 140) and was part of a larger project to investigate the prehistoric landscape of the area, with Bronze Age monuments and an Anglo-Saxon cemetery in the adjoining fields (Sherlock 2010). Two trenches had been opened and one of them (area D) contained evidence for a rectangular feature, with two associated areas of heating (figure 5.47). At the time of sample collection there was no diagnostic dating evidence that had been recovered from contexts associated with the rectangular structure, but the structure was similar to a Romano-British bread oven found locally. From the other trench some Samian ware had been recovered, suggesting that the rectangular feature may well be late Iron Age/early Romano-British in age.



*Figure 5.47: Overview of area D at Street House (looking north). AM132, context 899, is on the western edge of the stone platform (the white sampling buttons are still in situ; yellow circle). AM133, context 892, is the circular patch of stones south of the stone platform (light blue circle).*

Two features were chosen for sampling based on their state of preservation and evidence of firing. The first was an area of clay (AM132, context 889) along the western edge of the rectangular structure, butting an area of stones forming a platform (context 845) because there was evidence to suggest the clay had been heated (figure 5.48). There were a series of possible stake holes going to a depth of 10cm, surrounding a patch of charcoal (context 853). The natural clay was yellow but this patch was darker red/brown and, coupled with the proximity of charcoal, suggests that it had been heated. Context 889 was interpreted as an oven; however, there was extensive cracking within this area, which indicates some movement of material since last heating.



*Figure 5.48: AM132, context 889, the oven at Street House viewed from the east. Top is a schematic showing the location of the samples collected and bottom is a photograph showing the extensive cracking, believed to be the cause of the scatter observed in the magnetic directions. Moisture levels have been stated as a cause of less reliable archaeomagnetic results (Lange & Murphy 1990: 78) and cause rotation of the magnetic moment that cannot be removed (Henshaw & Merrill 1979).*

A total of 20 samples were collected from this feature and just over half of the samples for both features had a measureable remanence, indicating that not all of the material sampled contained sufficient magnetic minerals to record a stable magnetic direction or had not been heated to a sufficiently high temperature (table 5.25 and figure 5.49). This observation raises some concerns regarding the ability of these samples to produce a reliable archaeomagnetic direction because eight showed negative inclinations and low intensities, so did not undergo bulk demagnetisation. Analysis of the remaining 12 samples that were demagnetised showed that two samples (AM132/9 and AM132/10) were discordant and also determined that all of the samples from AM132 were classified as meta-stable (table 5.26). The most likely reason for this lack of stability is that when in use this feature did not reach temperatures high enough to cause the more stable magnetic minerals to record the contemporary geomagnetic field, suggesting that it has not recorded a consistent magnetic direction. It was also observed during the fieldwork that the feature had dried out during the interval between excavation and sampling. Previous studies have suggested that allowing a feature to dry out leads to less reliable archaeomagnetic results (Lange & Murphy 1990: 78), and can cause the magnetic moments to rotate (Henshaw & Merrill 1979), which will manifest as scatters in the recorded directions. These findings are consistent with the results from AM132.

<b>Magnetisation</b>	<b>Mean Dec (°)</b>	<b>Mean Inc (°)</b>	<b><math>\alpha_{95}</math></b>	<b>N</b>	<b>Demagnetisation field (mT)</b>	<b>No. of discordant samples</b>
NRM	7.4	12.9	25.6	20	7.5	-
ChRM	7.1	47.6	15.9	10	-	10

*Table 5.25: Summary of the mean NRM and ChRM for AM132 from Street House, data are at site co-ordinates.*

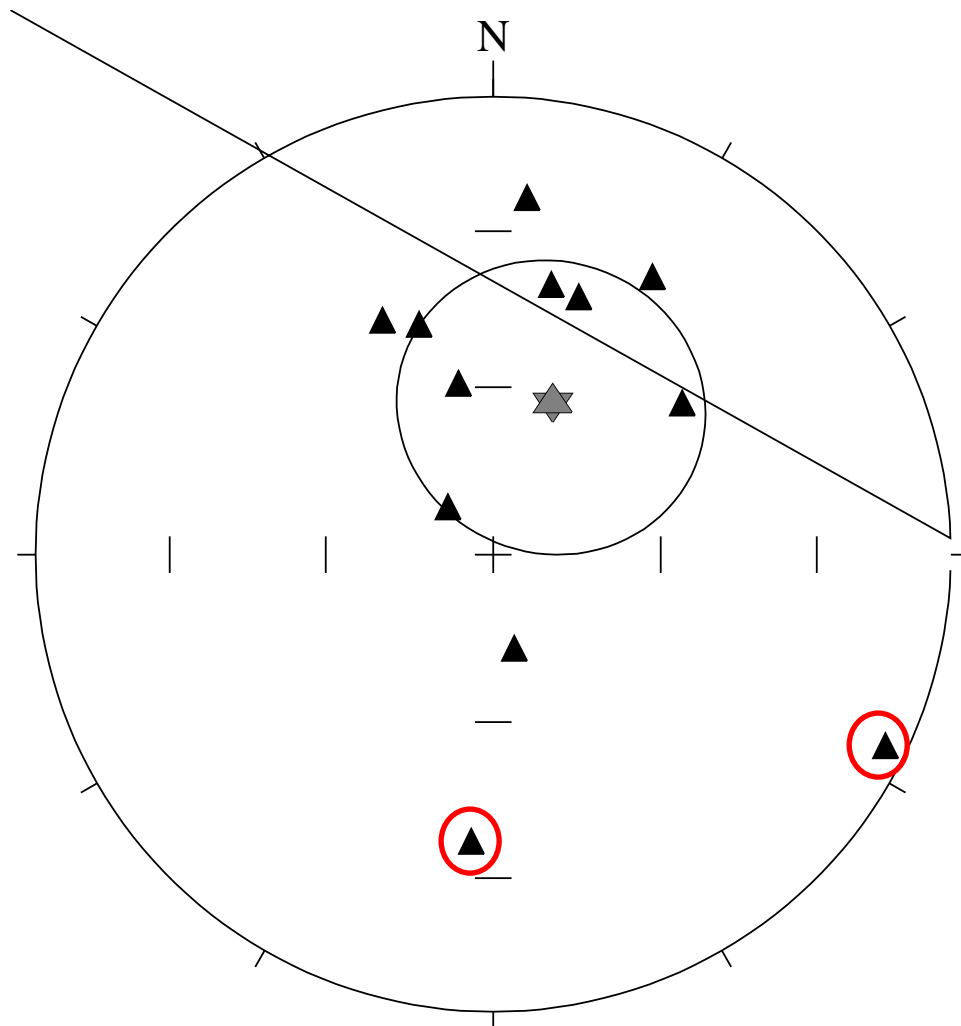
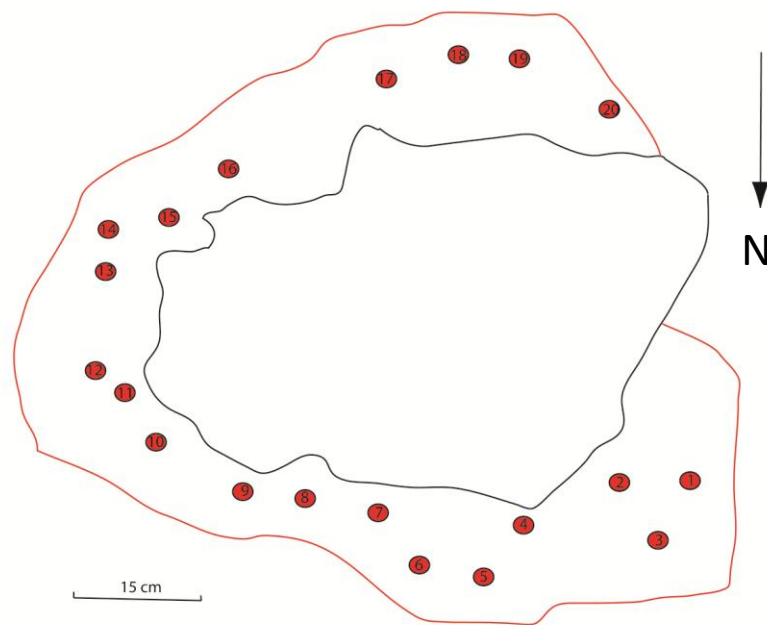


Figure 5.49: Stereoplot showing the ChRM of AM132 from Street House. Closed (open) symbols represent positive (negative) inclinations. In the northern hemisphere inclinations should be positive, so any individual directions with negative inclinations are rejected. The outliers that were removed are highlighted with red circles. The mean direction (including outliers) is shown by the grey star and the  $\alpha_{95}$  value shown as a circle.

Pilot sample reference	Reason for selecting	MDF (mT)	SI	% intensity remaining at 100mT
AM132/4	Potential outlier, higher intensity	11	0.8, meta-stable	1.2
AM132/10	Representative, higher intensity	12	0.8, meta-stable	0.7
AM132/14	Representative, lower intensity	9	0.6, meta-stable	1.7

Table 5.26: The results from the pilot demagnetisation of the oven at Street House to investigate the nature of the magnetic signal.

The second feature was located south of the stone platform and was a discrete area of flat stones (AM133, context 845), with an average diameter of 70cm, (figure 5.50). Context 845 had been identified as a stone lined hearth. Twenty samples were collected from the clay the stones had been set into, as there was a halo of reddening surrounding the stones. There was evidence for a 1.5m strip of charcoal and burnt material running away from this stone hearth and the rectangular stone platform.



*Figure 5.50: A schematic of AM133, context 892 the stone lined hearth at Street House showing the location of the samples collected.*

Eight of the samples displayed weak intensities and negative inclinations in their NRM values and so did not undergo bulk demagnetisation. The remaining magnetic data from AM133 (table 5.27) and further analysis (table 5.28 and figure 5.51) suggested that eleven of the samples collected recorded a consistent magnetic direction; AM133/16 was identified as being discordant from the rest of the samples.

Magnetisation	Mean Dec (°)	Mean Inc (°)	$\alpha_{95}$	N	Demagnetisation field (mT)	No. of discordant samples
NRM	5.6	34.9	33.1	20	7.5	-
ChRM	359.6	60.0	8.0	11	-	9

Table 5.27: Summary of the mean NRM and ChRM for AM133 from Street House, data are at site co-ordinates.

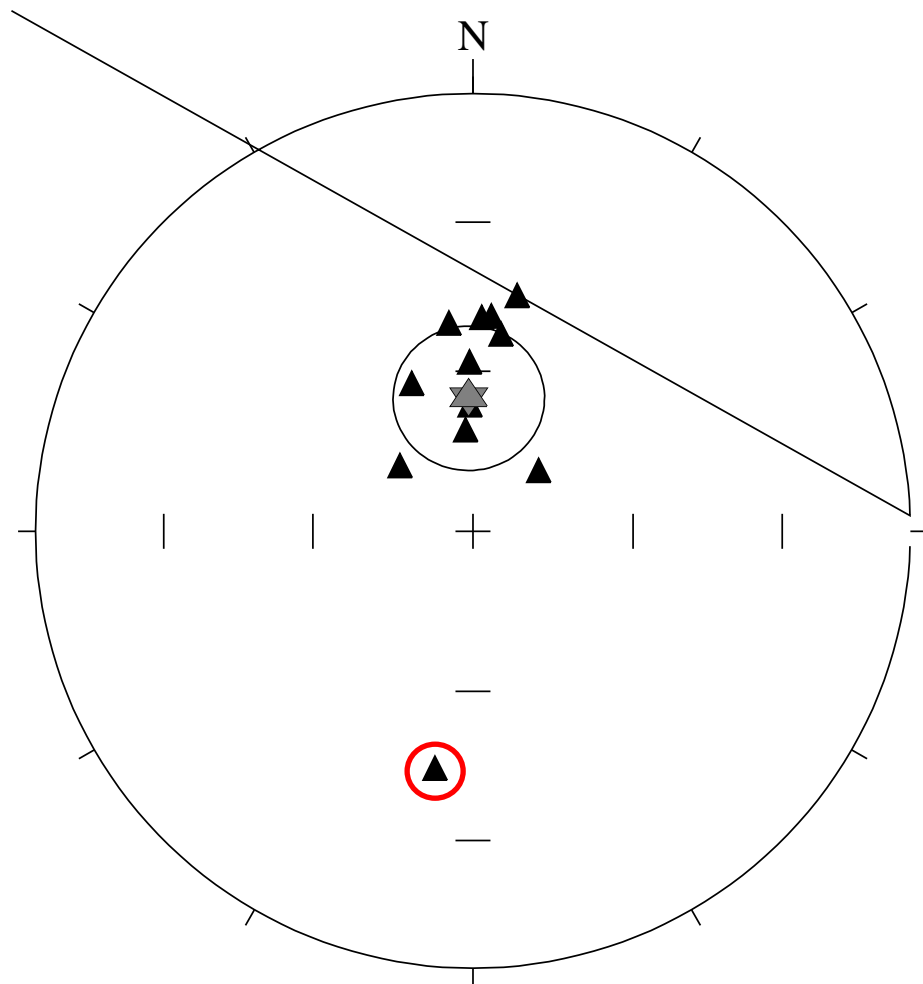


Figure 5.51: Stereoplot showing the ChRM of AM133 from Street House. Closed (open) symbols represent positive (negative) inclinations. In the northern hemisphere inclinations should be positive, so any individual directions with negative inclinations are rejected. The outlier that was removed is highlighted with a red circle. The mean direction (including outlier) is shown by the grey star and the  $\alpha_{95}$  value shown as a circle.

Pilot sample reference	Reason for selecting	MDF (mT)	SI	% intensity remaining at 100mT
AM133/1	Representative, higher intensity	12.5	2, poorly stable	2
AM133/10	Representative, higher intensity	7	3, stable	6
AM133/19	Potential outlier, lower intensity	12.5	0.5, meta-stable	2

*Table 5.28: The results from the pilot demagnetisation of the stone-lined hearth at Street House to investigate the nature of the magnetic signal.*

### **5.3.10 The Cairns: AM157, AM158, AM163, AM164, AM165 AM175 and AM176**

This site is located near to Cleat on the southern tip of South Ronaldsay (ND566955) and overlooks Wind Wick bay (figure 5.1 on page 140). The excavations are part of a larger project to investigate the prehistoric landscape of the area with another Iron Age settlement in the adjoining field (Carruthers, pers. comm. 2008). Excavations had revealed a large stone-built circular structure, potentially a broch, with evidence for several phases of use and adjoining buildings. This excavation is still on-going but there is some artefactual dating evidence, which suggests an Iron Age date for occupation at this site. This site was visited over three seasons and it was possible to collect samples in 2008, 2009 and 2010.

During the 2008 season, two features were chosen for sampling based on their state of preservation and evidence of firing. The first was an area of clay (AM157, context 279) at the eastern edge of the excavated area (figure 5.52). When excavated there was evidence to suggest that the clay had been a floor surface in a building and that the building had gone out of use, due to a fire, as there were burnt artefacts still *in situ*. The sampling focused on a halo of colour change surrounding a stone that showed evidence of fire cracking. The deposits ranged in colour from red (Munsell reference 10R 4/6) through to dusky red (Munsell



reference 10R 3/2) and dark reddish brown (Munsell reference 2.5YR 3/3); as much of the red material as possible was sampled.



*Figure 5.52: AM157, context 279, the burnt floor at The Cairns viewed from the north-east (scale 0.15m).*

A total of 20 samples were collected and the samples had a measureable remanence, indicating that the material sampled contained sufficient magnetic minerals to record a stable magnetic direction (table 5.29 and figure 5.53). More detailed analysis of the magnetic data determined that the magnetic direction of AM157 was consistent and stable (table 5.30) and further analysis identified no discordant results, which could be used to provide an archaeomagnetic direction.

Magnetisation	Mean Dec (°)	Mean Inc (°)	$\alpha_{95}$	N	Demagnetisation field (mT)	No. of discordant samples
NRM	3.2	72.7	2.8	20	2.5	-
ChRM	343.0	77.1	3.1	20	-	0

Table 5.29: Summary of the mean NRM and ChRM for AM157 from The Cairns, data are at site co-ordinates.

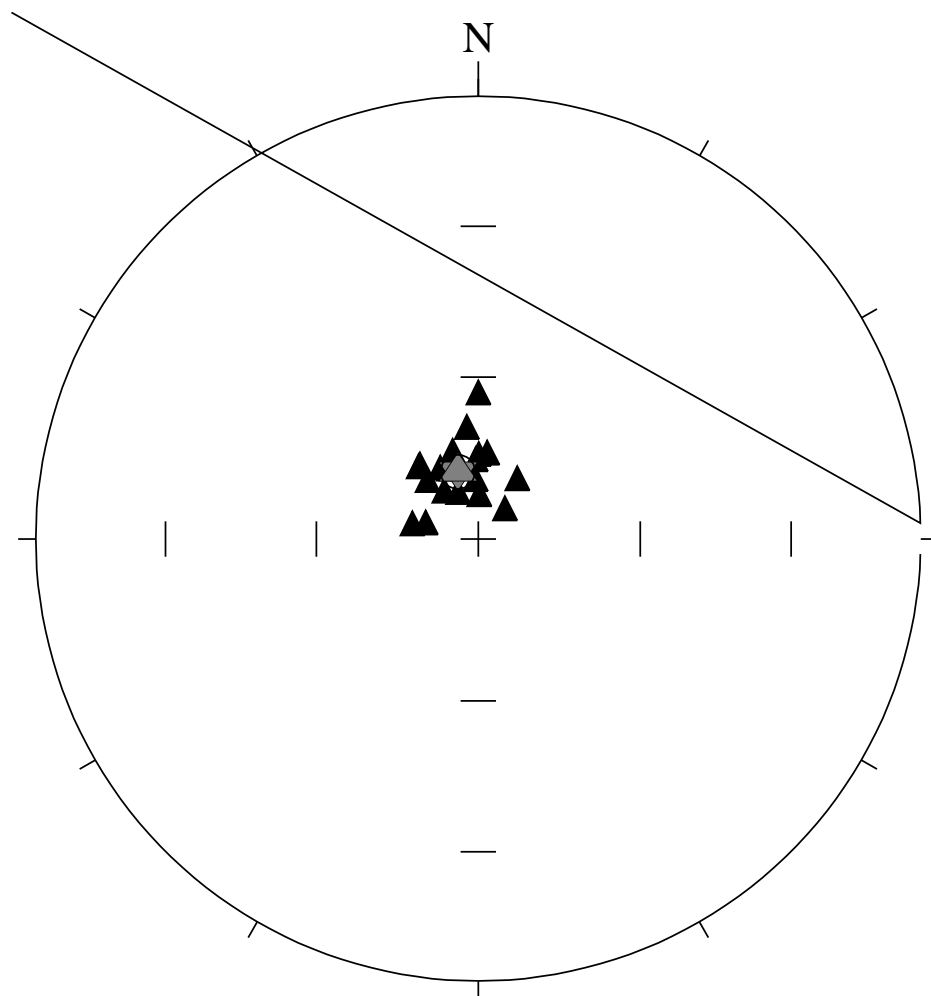


Figure 5.53: Stereoplot showing the ChRM of AM157 from The Cairns. Closed (open) symbols represent positive (negative) inclinations. In the northern hemisphere inclinations should be positive, so any individual directions with negative inclinations are rejected. The mean direction of the data plotted is shown by the grey star and the  $\alpha_{95}$  value shown as a circle.

Pilot sample reference	Reason for selecting	MDF (mT)	SI	% intensity remaining at 100mT
AM157/1	Representative	15	9, very stable	7
AM157/2	Representative, lower intensity	17.5	8, very stable	12
AM157/12	Representative, highest intensity	17.5	9, very stable	6
AM157/20	Representative	12	7, very stable	5

*Table 5.30: The results from the pilot demagnetisation of the burnt floor from The Cairns to investigate the nature of the magnetic signal.*

The second feature sampled in 2008 was a formal hearth within a rectangular building, structure B (AM158 context 183); (figure 5.54). The hearth was rectangular, lined with a large stone which showed effects of heating and kerbed with small upright slabs. The western edge had been constructed with a broken quern stone and two hammer stones formed the corners. Samples were collected from the hearth fill, which was a reddish black (Munsell reference 10R 2.5/1) ash rich clay matrix (context 183). Twenty samples were collected from this feature and the samples had a measureable remanence, indicating that the material sampled contained sufficient magnetic minerals to record a stable magnetic direction. Detailed analysis of the magnetic direction from AM158 demonstrated that, although stable (tables 5.31 and 5.32), it was scattered (figure 5.55), which was probably due to the effect of weathering and associated slumping of the ashy material sampled, due to exposure for several months before sampling for archaeomagnetism took place (figure 5.54). Two samples had negative inclinations (AM158/2 and AM158/3) and one sample (AM158/17) was found to be discordant.





*Figure 5.54: Two images of AM158, context 183; the stone lined hearth at The Cairns viewed from the south. The top image shows the hearth as it was excavated. The bottom image shows the condition of the hearth when the samples were collected some months later (scale 0.15m). These images illustrate the need to either protect the feature between excavation and sampling for archaeomagnetism or keep the time between the two to a minimum for the best archaeomagnetic results (Top photograph © Martin Carruthers, Orkney College).*

Magnetisation	Mean Dec (°)	Mean Inc (°)	$\alpha_{95}$	N	Demagnetisation field (mT)	No. of discordant samples
NRM	42.9	69.1	17.7	20	5	-
ChRM	35.6	70.9	10.2	17	-	3

Table 5.31: Summary of the mean NRM and ChRM for AM158 from The Cairns, data are at site co-ordinates.

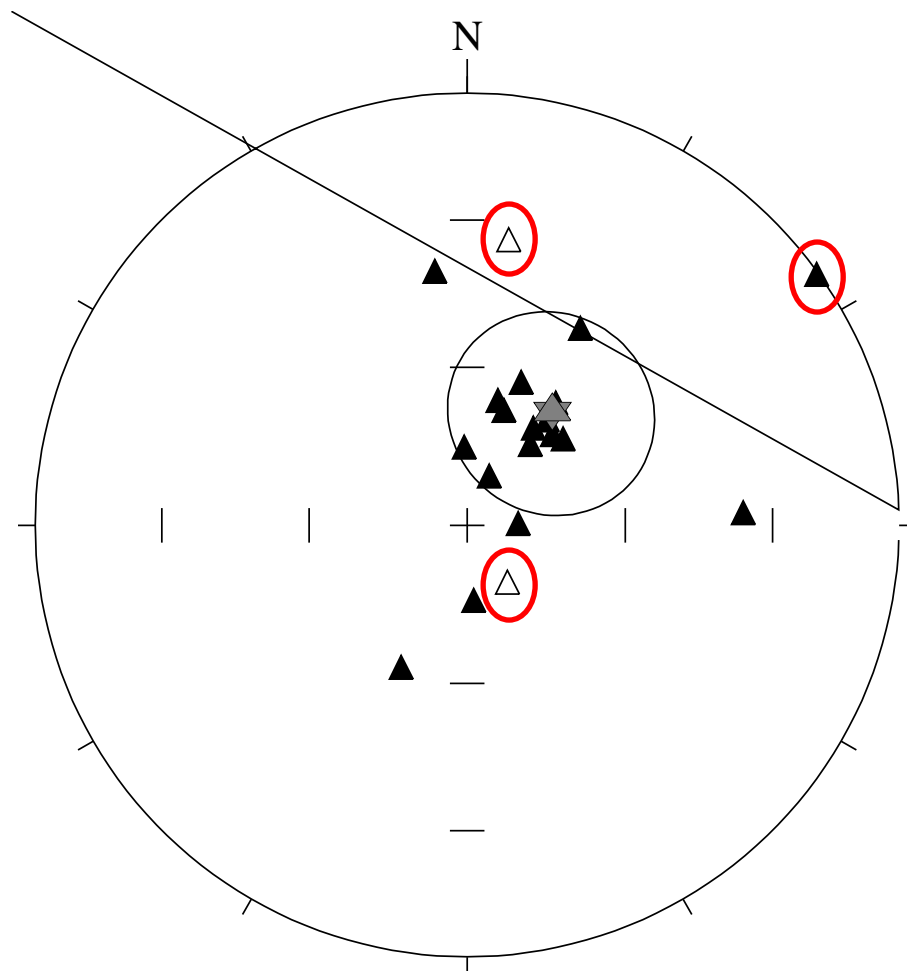


Figure 5.55: Stereoplot showing the ChRM of AM158 from The Cairns. Closed (open) symbols represent positive (negative) inclinations. In the northern hemisphere inclinations should be positive, so any individual directions with negative inclinations are rejected. The outliers that were removed are highlighted with red circles. The mean direction (including outliers) is shown by the grey star and the  $\alpha_{95}$  value shown as a circle.

<b>Pilot sample reference</b>	<b>Reason for selecting</b>	<b>MDF (mT)</b>	<b>SI</b>	<b>% intensity remaining at 100mT</b>
AM158/5	Potential outlier, lower intensity	12.5	6, very stable	3
AM158/10	Representative, highest intensity	12.5	8, very stable	3
AM158/12	Representative, lower intensity	10	3, stable	4
AM158/17	Potential outlier, higher intensity	12.5	2, poorly stable	12

*Table 5.32: The results from the pilot demagnetisation of the stone-lined hearth at The Cairns to investigate the nature of the magnetic signal.*

During the 2009 season three features from an area called Structure C were chosen for sampling based on their state of preservation and evidence of exposure to heat (figure 5.56). The first was an area of clay (AM163, context 279) which appears to seal the eastern circuit of the broch tower (figure 5.57). AM163 is an extension of the possible burnt floor surface in a building that was sampled in October 2008. The sampling focused on the area of greatest colour change, which appeared as two patches. The deposits ranged in colour from reddish brown (Munsell reference 5YR 4/3) through to dusky red (Munsell reference 10R 3/2) and dark reddish brown (Munsell reference 5YR 3/4); as much of the red material as possible was sampled.

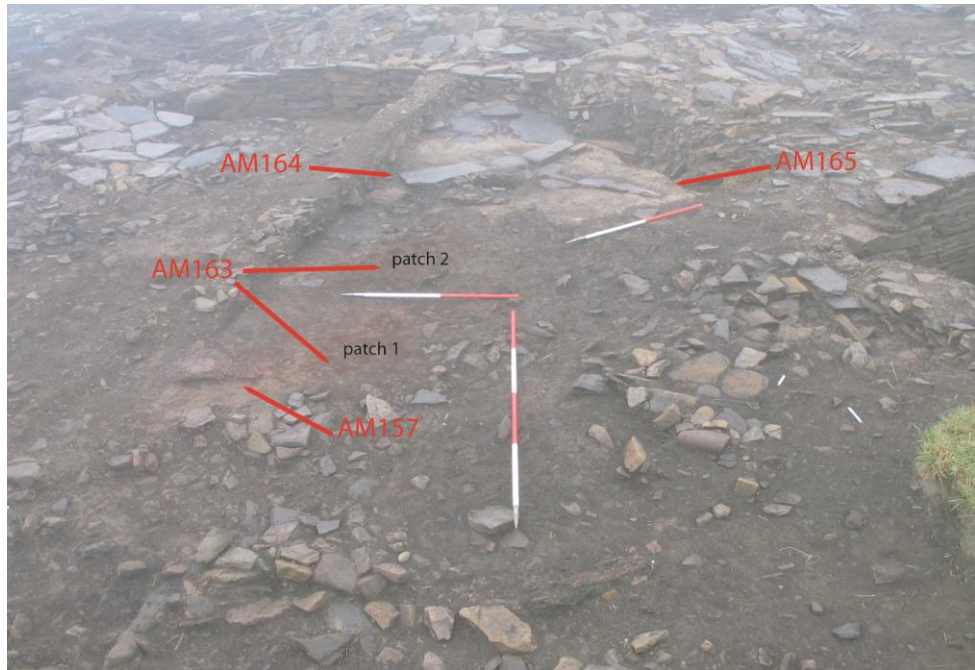


Figure 5.56: Overview of Structure C at The Cairns viewed from the east, showing the location of all the features sampled during summer 2009 and how they relate to AM157 collected the previous year (scale 1m).

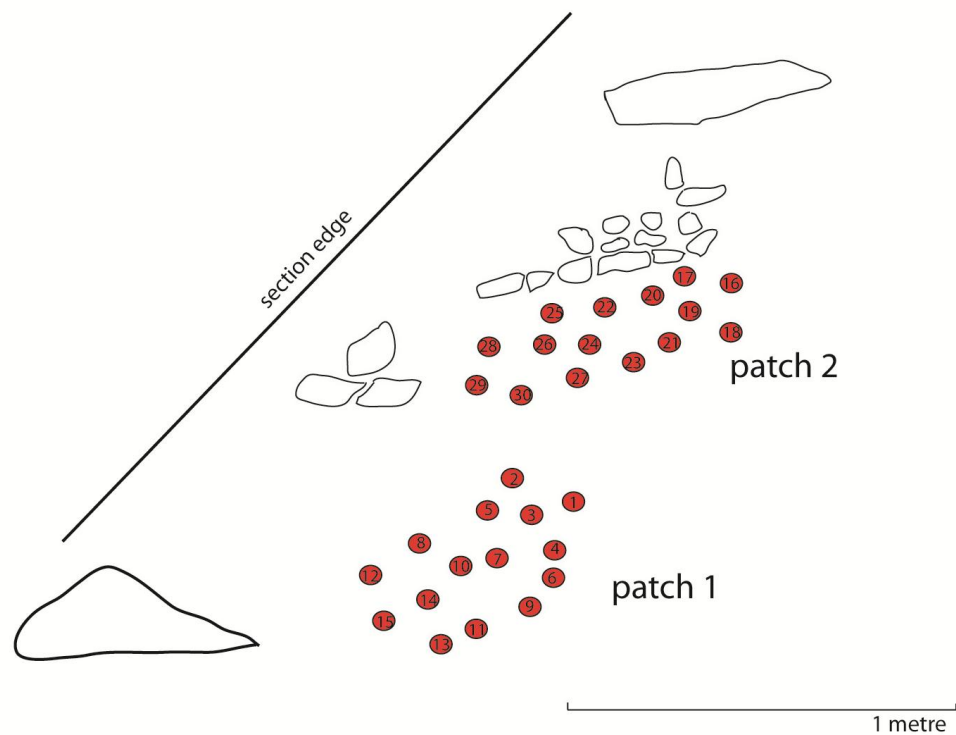
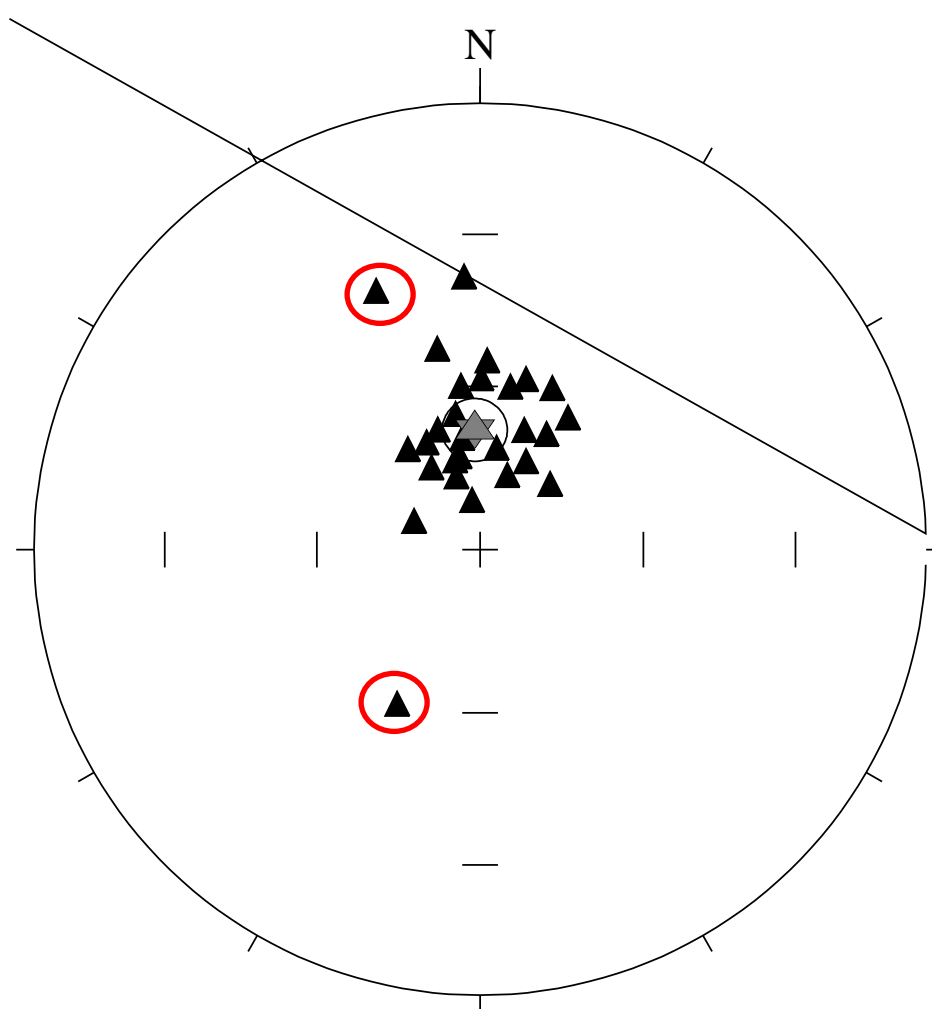


Figure 5.57: AM163, context 279; a schematic showing the location of the samples collected from the burnt floor at The Cairns.



A total of 29 samples were collected from context 279 (AM163) and all the samples collected had a measureable remanence (table 5.33 and figure 5.58), indicating that the material sampled contained sufficient magnetic minerals to record a stable magnetic direction. Sample AM163/20 detached from the orientation button and so did not undergo bulk demagnetisation. More detailed analysis of the magnetic data determined that two samples were discordant (AM163/11 and AM163/22) but the rest of the magnetic directions were consistent (table 5.34) and so could be used to provide an archaeomagnetic direction.



*Figure 5.58: Stereoplot showing the ChRM of AM163 from The Cairns. Closed (open) symbols represent positive (negative) inclinations. In the northern hemisphere inclinations should be positive, so any individual directions with negative inclinations are rejected. The outliers that were removed are highlighted with red circles. The mean direction (including outliers) is shown by the grey star and the  $\alpha_{95}$  value shown as a circle.*



<b>Magnetisation</b>	<b>Mean Dec (°)</b>	<b>Mean Inc (°)</b>	<b><math>\alpha_{95}</math></b>	<b>N</b>	<b>Demagnetisation field (mT)</b>	<b>No. of discordant samples</b>
NRM	350.5	59.5	13.1	29	7.5	-
ChRM	0.6	67.4	4.5	26	-	3

*Table 5.33: Summary of the mean NRM and ChRM for AM163 from The Cairns, data are at site co-ordinates.*

<b>Pilot sample reference</b>	<b>Reason for selecting</b>	<b>MDF (mT)</b>	<b>SI</b>	<b>% intensity remaining at 100mT</b>
AM163/3	Patch 1 negative inclination, lower intensity	17	2, poorly stable	4
AM163/7	Patch 1 representative, higher intensity	15	0.7, meta-stable	19
AM163/8	Patch 1 potential outlier, lower intensity	15	1, meta-stable	4
AM163/11	Patch 1 potential outlier, higher intensity	15	1, meta-stable	6
AM163/12	Patch 1 representative, lower intensity	28	1, meta-stable	45
AM163/19	Patch 2 representative, higher intensity	15	0.4, unstable	10
AM163/22	Patch 2 potential outlier, lower intensity	15	0.4, unstable	2
AM163/23	Patch 2 representative, higher intensity	15	5, stable	6

*Table 5.34: The results from the pilot demagnetisation of the burnt floor from The Cairns to investigate the nature of the magnetic signal.*

The second feature sampled in 2009 was a patch of potentially heat affected clay (AM164, context 395) at the southern edge of what appeared to be a rectangular area of yellow clay (figure 5.59). AM164 was half a metre west of context 279. The regular patch of yellow clay contained a T-shaped arrangement of flag stones and some iron objects were recovered from the vicinity. The burnt patch

ranged in colour from red (Munsell reference 2.5YR 4/6) to dark reddish-brown (Munsell reference 2.5YR 3/3).



*Figure 5.59: AM164, context 395; southern area of burning at The Cairns viewed from the south (scale 0.2m).*

A total of 16 samples were collected from context 395 (AM164). All of the samples collected had a measureable remanence (table 5.35 and figure 5.60), indicating that the material sampled contained sufficient magnetic minerals to record a stable magnetic direction. More detailed analysis of the magnetic data determined that only one sample was discordant (AM164/7) and that the other magnetic directions were consistent (table 5.36) and so could be used to provide an archaeomagnetic direction.

Magnetisation	Mean Dec (°)	Mean Inc (°)	$\alpha_{95}$	N	Demagnetisation field (mT)	No. of discordant samples
NRM	340.4	75.9	7.4	16	7.5	-
ChRM	11.1	68.8	3.9	15	-	1

Table 5.35: Summary of the mean NRM and ChRM for AM164 from The Cairns, data are at site co-ordinates.

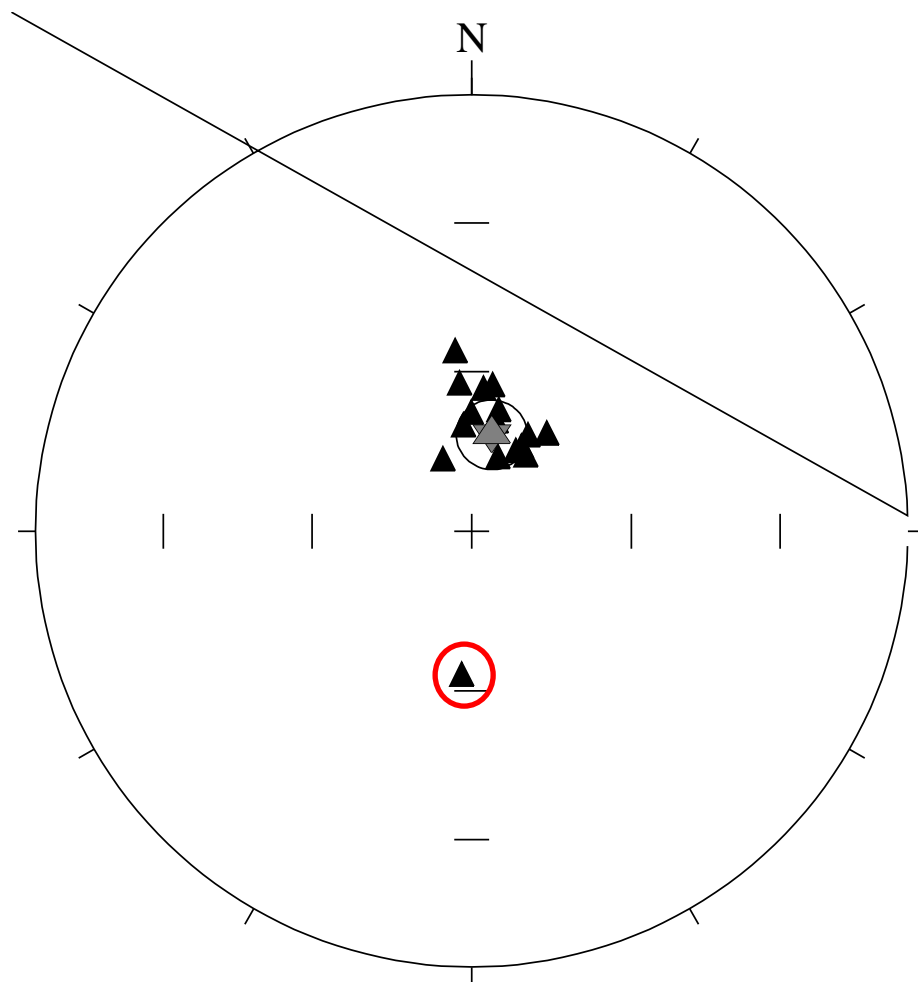


Figure 5.60: Stereoplot showing the ChRM of AM164 from The Cairns. Closed (open) symbols represent positive (negative) inclinations. In the northern hemisphere inclinations should be positive, so any individual directions with negative inclinations are rejected. The outlier that was removed is highlighted with a red circle. The mean direction (including outlier) is shown by the grey star and the  $\alpha_{95}$  value shown as a circle.

Pilot sample reference	Reason for selecting	MDF (mT)	SI	% intensity remaining at 100mT
AM164/1	Representative, higher intensity	15	4, stable	6
AM164/6	Representative, lower intensity	12.5	5, stable	5
AM164/7	Potential outlier, lowest intensity	10	0.5, meta-stable	5
AM164/11	Representative, highest intensity	12.5	6, very stable	7

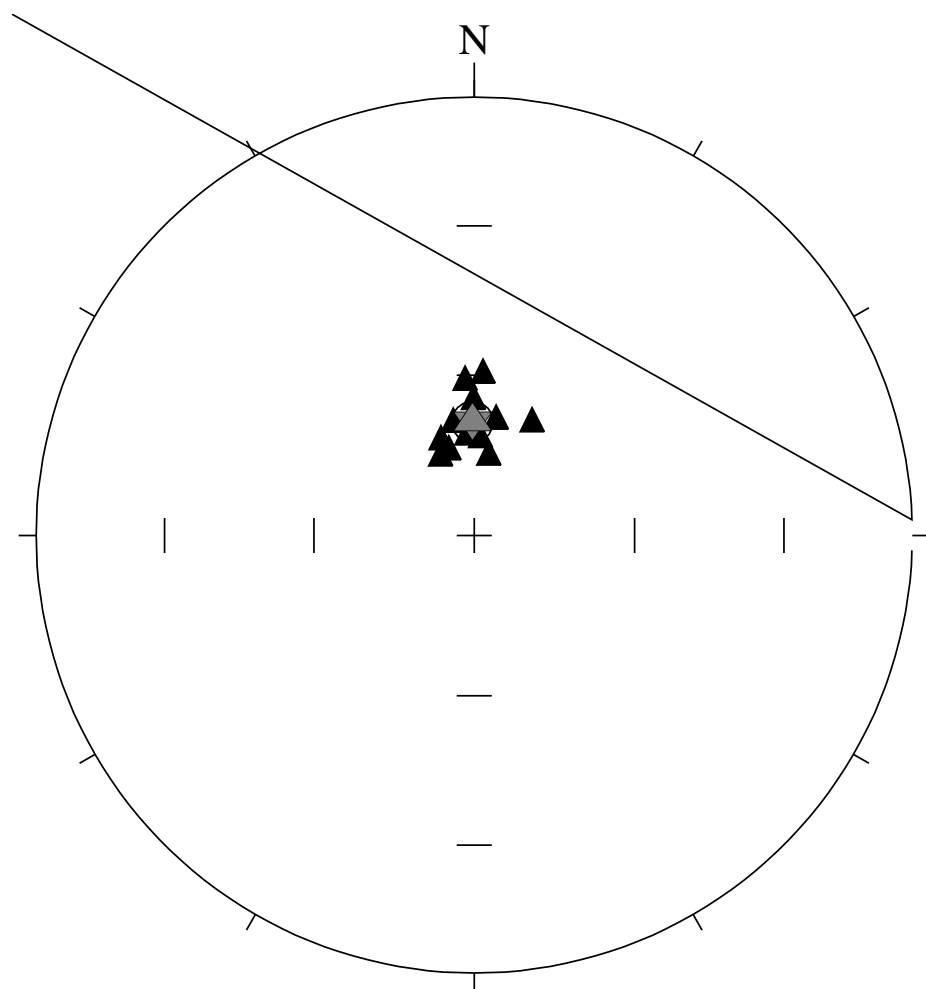
*Table 5.36: The results from the pilot demagnetisation of the southern area of burning at The Cairns to investigate the nature of the magnetic signal.*

The final feature sampled in 2009 was another patch of heat affected clay, at the northern edge of the regular patch of yellow clay (AM165, context 051; figure 5.61). This area of burning was at the tip of the T-arrangement of stones within the yellow clay and ranged in colour from pink (Munsell reference 5YR 7/3) to reddish yellow (Munsell reference 5YR 6/6).



*Figure 5.61: AM165, context 051, the northern area of burning at The Cairns viewed from the south (scale 0.2m).*

A total of 14 samples were collected from context 051 (AM165). All of the samples collected had a measureable remanence (table 5.37 and figure 5.62), indicating that the material sampled contained sufficient magnetic minerals to record a stable magnetic direction. More detailed analysis of the magnetic data determined that no samples were discordant such that all of the magnetic directions were consistent (table 5.38), and so could be used to provide an archaeomagnetic direction.



*Figure 5.62: Stereoplot showing the ChRM of AM165 from The Cairns. Closed (open) symbols represent positive (negative) inclinations. In the northern hemisphere inclinations should be positive, so any individual directions with negative inclinations are rejected. The mean direction is shown by the grey star and the  $\alpha_{95}$  value shown as a circle.*

<b>Magnetisation</b>	<b>Mean Dec (°)</b>	<b>Mean Inc (°)</b>	<b><math>\alpha_{95}</math></b>	<b>N</b>	<b>Demagnetisation field (mT)</b>	<b>No. of discordant samples</b>
NRM	4.8	60.5	4.8	12	5	-
ChRM	359.1	68.8	3.8	12	-	0

*Table 5.37: Summary of the mean NRM and ChRM for AM165 from The Cairn, data are at site co-ordinates.*

<b>Pilot sample reference</b>	<b>Reason for selecting</b>	<b>MDF</b>	<b>SI</b>	<b>% intensity remaining at 100mT</b>
AM165/1	Potential outlier, higher intensity	12.5	1, meta-stable	1
AM165/3	Representative, higher intensity	12.5	2, poorly stable	2
AM165/7	Representative, lower intensity	12.5	0.5, meta-stable	1
AM165/10	Potential outlier, lower intensity	12.5	2, poorly stable	2

*Table 5.38: The results from the pilot demagnetisation of the northern area of burning at the Cairns to investigate the nature of the magnetic signal.*

Since all three features sampled were found in close proximity it was decided to compare the magnetic directions to see if they all recorded the same direction. It is worth bearing in mind that the hearth (AM164) displayed magnetic properties consistent with a stable signal whereas with the flue (AM165) and burnt floor (AM163) magnetic properties suggested a less stable signal. The comparison was done by comparing the ChRM mean directions (tables 5.33, 5.35 and 5.37), utilising the statistical procedure developed in palaeomagnetic studies (McFadden & Lowes 1981; McFadden & McElhinny 1990), which revealed that all three features had recorded the same magnetic direction at 95% confidence level. This similarity suggests that for all three features the last heating event was possibly a contemporary event and is consistent with the archaeological interpretation of this

area as a workshop. Finally, because AM157, sampled in October 2008, was in close proximity to the location of AM163, sampled July 2009, it was decided to compare these two ChRM mean directions as well (table 5.29 and 5.33). This comparison revealed that they do not record the same magnetic direction at 95% confidence level. It is suggested that this difference may be explained by weathering of the material sampled (Lange & Murphy 1990: 78) because the laboratory results suggest that the signal was stable. The area sampled for AM157 had been left uncovered for three months prior to sampling, whereas the area sampled for AM163 had only just been revealed by excavation and care had been taken to minimise any disturbance, from the sediment drying out or walking over the surface, before sampling commenced. This approach yielded positive results as the magnetic direction was suitable to obtain a calibrated archaeomagnetic date.

During the 2010 season a stone-lined hearth feature, discovered the previous year and that had been kept covered, was sampled following the protocols suggested by Lange and Murphy (1990: 80). During this season's fieldwork the hearth feature had been half sectioned, which revealed that it contained heated deposits. Excavation had also demonstrated that this hearth sealed the broch wall. Two contexts with evidence for heating had been identified within the hearth fill, 803 and 804; both of these were sealed by several lenses of charcoal, which in turn were covered by a mixed stony layer (figure 5.63). At this stage each context was sampled and treated separately, the upper fill, 803 (AM175), was a red-ash clay, containing small stones, and the lower fill, 804 (AM176), was very similar to 803 but contained fewer stones and had a higher concentration of ash. Both contexts ranged in colour from weak red (Munsell reference 10R 4/3) to dark red (Munsell reference 10R 3/6).





*Figure 5.63: Images showing the hearth feature (top) and the heat affected contexts that were sampled (bottom)(scale 0.5m) (Photographs © Robert Friel).*



A total of 23 samples were taken from cleaned horizontal surfaces, 12 from context 803 (AM175) and 11 from context 804 (AM176), using the standard tube method, because the materials were moist and soft. In this case sampling was undertaken by Zoe Outram and the photographic record is courtesy of Robert Friel. Both recorded magnetic directions (AM175 - table 5.39 and figure 5.64; AM176 – table 5.41 and figure 5.65) and more detailed analysis of the magnetic data determined that the magnetic direction from both contexts were consistent (AM 175 – table 5.40; AM176 – table 5.42) and so can be used to provide a mean archaeomagnetic direction.

<b>Magnetisation</b>	<b>Mean Dec (°)</b>	<b>Mean Inc (°)</b>	<b><math>\alpha_{95}</math></b>	<b>N</b>	<b>Demagnetisation field (mT)</b>	<b>No. of discordant samples</b>
NRM	26.3	76.0	2.9	12	5	-
ChRM	18.7	80.8	3.7	12	-	0

*Table 5.39: Summary of the mean NRM and ChRM for AM175 from The Cairns, data are at site co-ordinates.*

<b>Pilot sample reference</b>	<b>Reason for selecting</b>	<b>MDF</b>	<b>SI</b>	<b>% intensity remaining at 100mT</b>
AM175/3	Representative, lower intensity	16	7.2, very stable	13
AM175/4	Representative, higher intensity	17.5	6.0, very stable	4
AM175/8	Representative, mid intensity	12.5	6.1, very stable	7

*Table 5.40: The results from the pilot demagnetisation of the upper context, 803, in the hearth sampled in 2010 at the Cairns to investigate the nature of the magnetic signal.*

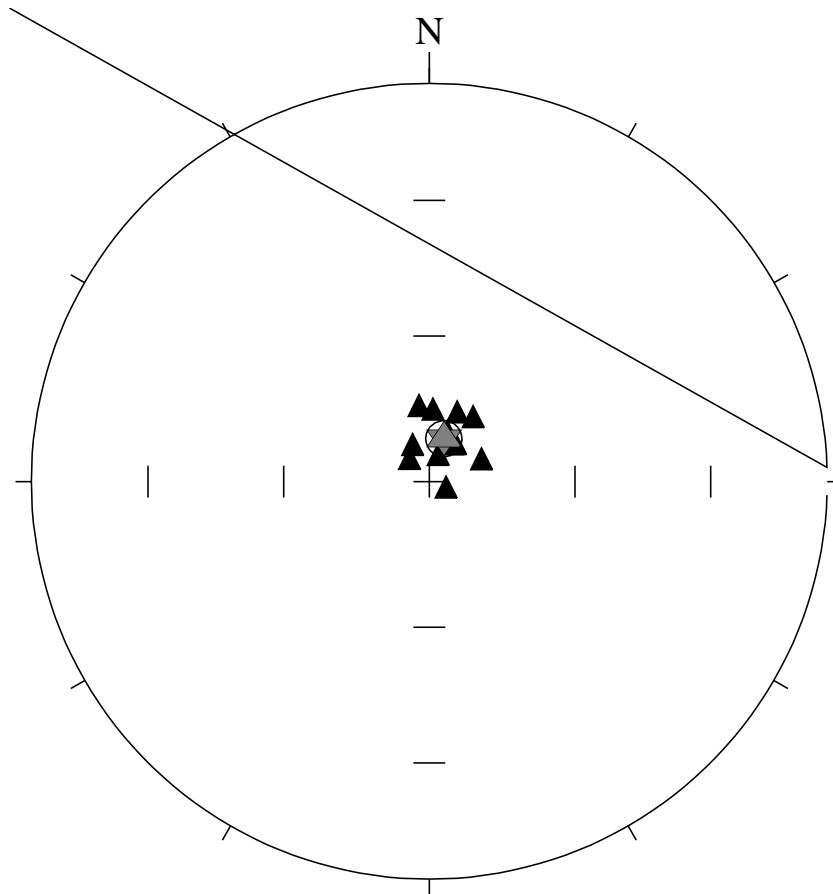


Figure 5.64: Stereoplot showing the ChRM of AM175 from The Cairns. Closed (open) symbols represent positive (negative) inclinations. In the northern hemisphere inclinations should be positive, so any individual directions with negative inclinations are rejected. The mean direction (including outliers) is shown by the grey star and the  $\alpha_{95}$  value shown as a circle.

Magnetisation	Mean Dec (°)	Mean Inc (°)	$\alpha_{95}$	N	Demagnetisation field (mT)	No. of discordant samples
NRM	17.6	78.7	4.7	11	2.5	-
ChRM	5.5	81.1	3.3	11	-	0

Table 5.41: Summary of the mean NRM and ChRM for AM176 from The Cairns, data are at site co-ordinates.

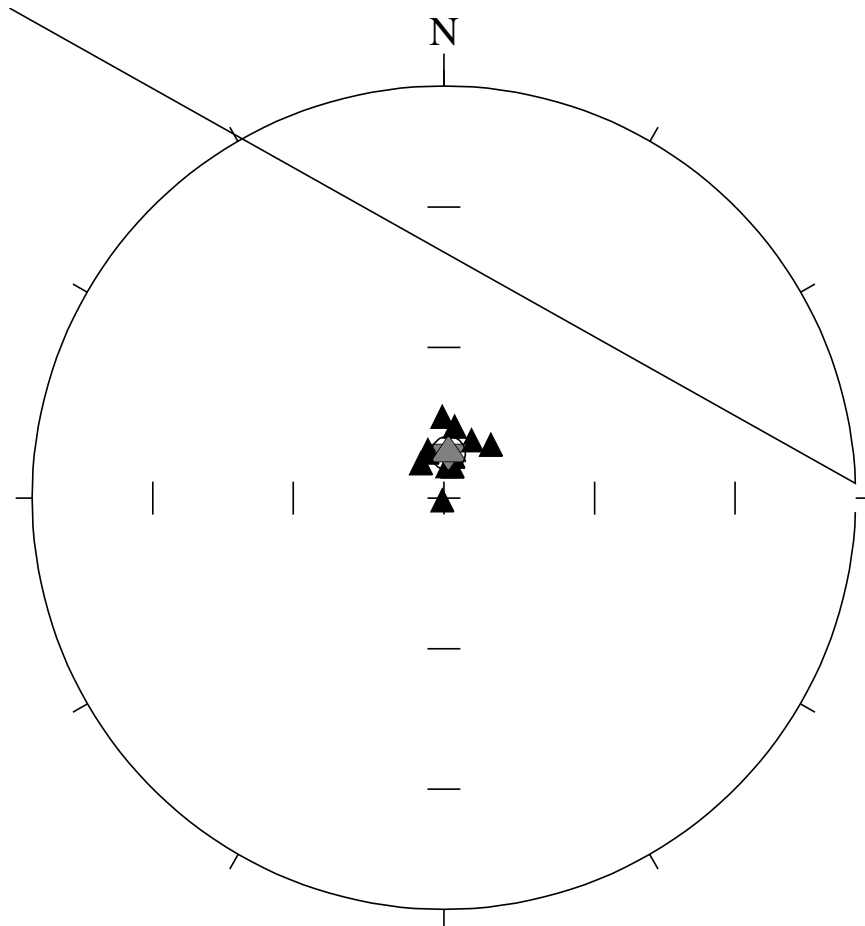


Figure 5.65: Stereoplot showing the ChRM of AM176 from The Cairns. Closed (open) symbols represent positive (negative) inclinations. In the northern hemisphere inclinations should be positive, so any individual directions with negative inclinations are rejected. The mean direction (including outliers) is shown by the grey star and the  $\alpha_{95}$  value shown as a circle.

Pilot sample reference	Reason for selecting	MDF	SI	% intensity remaining at 100mT
AM176/2	Representative, lower intensity	15	4.5, stable	10
AM176/9	Representative, higher intensity	7.5	4.8, stable	5
AM176/11	Representative, higher intensity	5	4.2, stable	4

Table 5.42: The results from the pilot demagnetisation of the lower context, 804, in the hearth sampled in 2010 at the Cairns to investigate the nature of the magnetic signal.

Since both of the contexts sampled were recovered from the same hearth feature, and that 803 (AM175) sealed 804 (AM176), it was decided to compare the ChRM mean directions to see if they both recorded the same direction (tables 5.39 and 5.41). The comparison was done by comparing the magnetic directions utilising the statistical procedure developed in palaeomagnetic studies (McFadden & Lowes 1981; McFadden & McElhinny 1990), which revealed that there was no significant difference between the magnetic directions recorded in these two contexts at 95% confidence; therefore it was possible to combine both directions (AM175&6) and this combined direction was used for this feature and put into the British archaeomagnetic database (figure 5.66 and table 5.43).

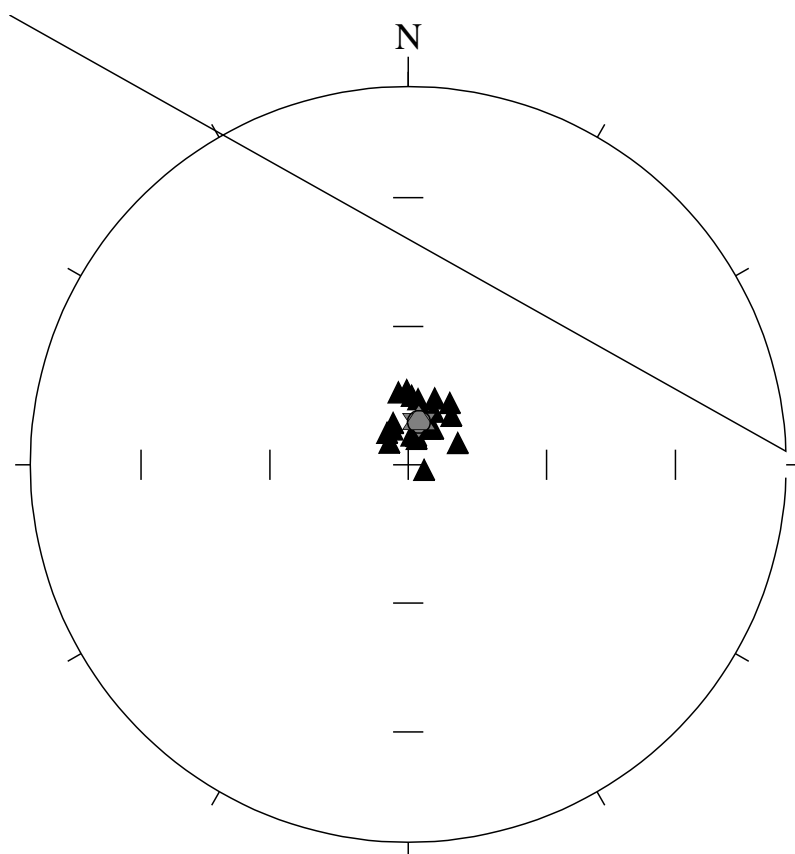


Figure 5.66: Stereoplot showing the ChRM of AM175&6 from The Cairns. Closed (open) symbols represent positive (negative) inclinations. In the northern hemisphere inclinations should be positive, so any individual directions with negative inclinations are rejected. The mean direction is shown with the star and the  $\alpha_{95}$  value shown as a circle. The mean direction is shown by the grey star and the  $\alpha_{95}$  value shown as a circle.

<b>Magnetisation</b>	<b>Mean Dec (°)</b>	<b>Mean Inc (°)</b>	<b><math>\alpha_{95}</math></b>	<b>N</b>	<b>Demagnetisation field (mT)</b>	<b>No. of discordant samples</b>
ChRM	12.5	81.0	2.4	23	-	0

*Table 5.43: Summary of the mean ChRM for AM175&6 from The Cairns, data are at site co-ordinates.*

### **5.3.11 Tŷ Mawr: AM81, AM82 and AM83**

Tŷ Mawr, near Holyhead (SH255807; figure 5.1 on page 140), was undergoing extensive land stripping and excavation during 2007 as part of the landscape preparations for a business development managed by Atkins Global. The excavation revealed a cluster of five well-preserved domestic structures interpreted as Iron Age roundhouses, indicative of an established long-term settlement. These were dated to the first millennium B.C. on the basis of the architecture and previous archaeological finds in the surrounding area. A total of three areas of burning were sampled; these features were uncovered in close proximity to each other, but displayed differing degrees of preservation. Two areas of burning were revealed within the domestic structures, roundhouses B (AM82, context 91972) and E (AM83, context 92141). About 15 metres east of the roundhouses there was an additional area of burning (AM81, context 91579). Since the roundhouse area was to be fully excavated to enable the infrastructure for the business park to be installed, it was possible to completely sample the features. However, because not all of the features had been fully recorded at the time of sampling, only twenty samples were taken from the exposed surfaces of each context.

***Eastern Area (EA): AM81, context 91579***

Context 91579 was an isolated patch of reddened material that appeared to have been subjected to heating (figure 5.67). This context was reddish-brown silty clay with orange patches towards the edges. Along the eastern edge of the deposit there was evidence for root activity NS so this area was avoided during sampling. Although this context was compacted *in situ* it was extremely friable, unlike the material associated with the roundhouses, BECAUSE the clay context was lower. At the time of sampling it was unclear if this context was associated with some potential Neolithic earthworks (ditches and post holes), post medieval activity (a stone spread and midden pits) or with the roundhouses.



*Figure 5.67: AM81; Eastern Area at Tŷ Mawr viewed from south showing the sample locations (scale 1m).*

The twenty samples collected from the eastern area were weakly magnetised and displayed a lot of scatter in the recorded magnetic direction (table 5.44 and figure 5.68).

Magnetisation	Mean Dec (°)	Mean Inc (°)	$\alpha_{95}$	N	Demagnetisation field (mT)	No. of discordant samples
NRM	82.0	77.5	32.7	7	-	-

Table 5.44: Summary of the mean NRM for AM81 from Tŷ Mawr; the magnetic directions showed too much scatter to identify a mean direction. Data are at site co-ordinates.

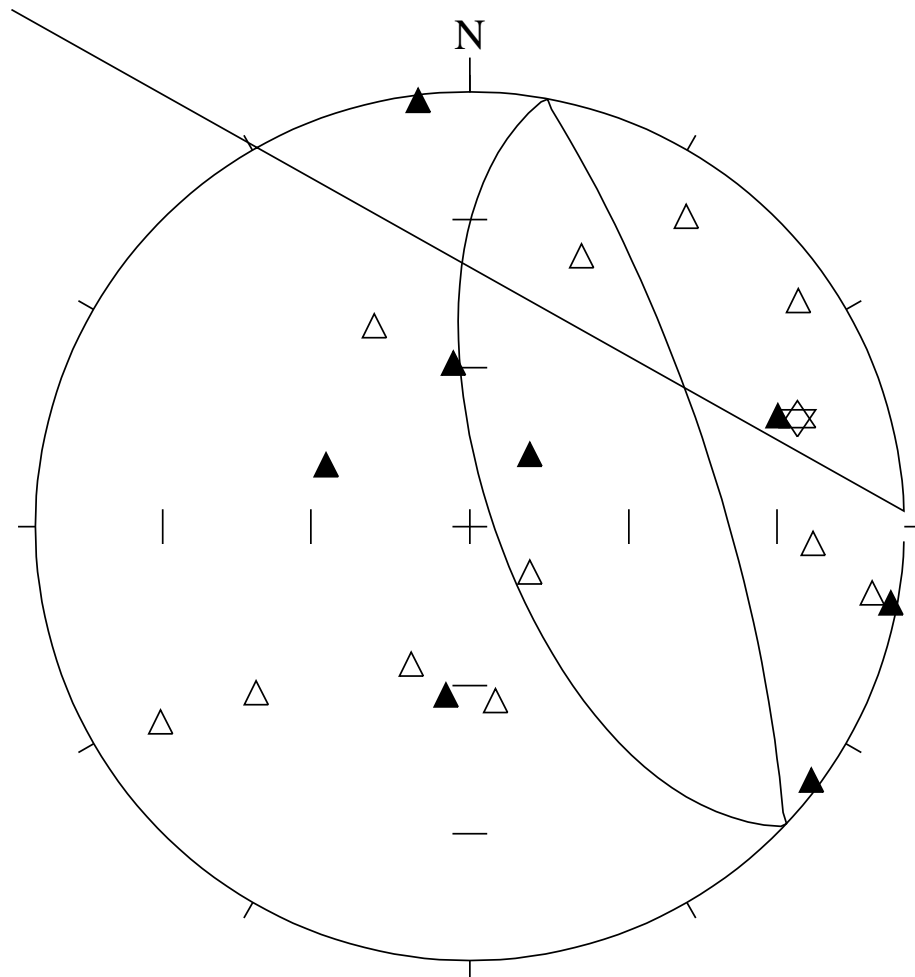


Figure 5.68: Stereoplot showing the NRM of AM81 from Tŷ Mawr. Closed (open) symbols represent positive (negative) inclinations. In the northern hemisphere inclinations should be positive, so any individual directions with negative inclinations are rejected. The mean direction is shown by the grey star and the  $\alpha_{95}$  value shown as a circle.

***Roundhouse B (RHB): AM82, context 91972***

In roundhouse B the area of burning was central to the structure and appeared to be associated with the first phase of occupation. There were two other earlier “hearths” over context 91972 but these had already been removed. The material sampled appeared to be cemented clay and was a pale yellow colour with infrequent patches of white and dark orange (figure 5.69), which suggested that the material might not contain enough magnetic minerals present to record the Earth’s magnetic signal during cooling, or that it has not been heated to a sufficient temperature to cause magnetic changes. However, the burnt area was covered by a large fire-cracked stone so this suggested that heating had taken place. It was decided that as the context was free from inclusions, had a high clay content and appeared to be *in situ*, it was suitable for sampling.



*Figure 5.69: AM82; Roundhouse B at Tŷ Mawr viewed from west showing the sample locations (scale 0.5m).*



The seventeen samples collected from the heated feature in roundhouse B were weakly magnetised and again displayed a lot of scatter in the recorded magnetic direction (table 5.45 and figure 5.70).

Magnetisation	Mean Dec (°)	Mean Inc (°)	$\alpha_{95}$	N	Demagnetisation field (mT)	No. of discordant samples
NRM	13.9	59.8	31.9	17	-	-

Table 5.45: Summary of the mean NRM for AM82 from Tŷ Maw; the magnetic directions showed too much scatter to identify a reliable mean direction for archaeomagnetic dating purposes, data are at site co-ordinates.

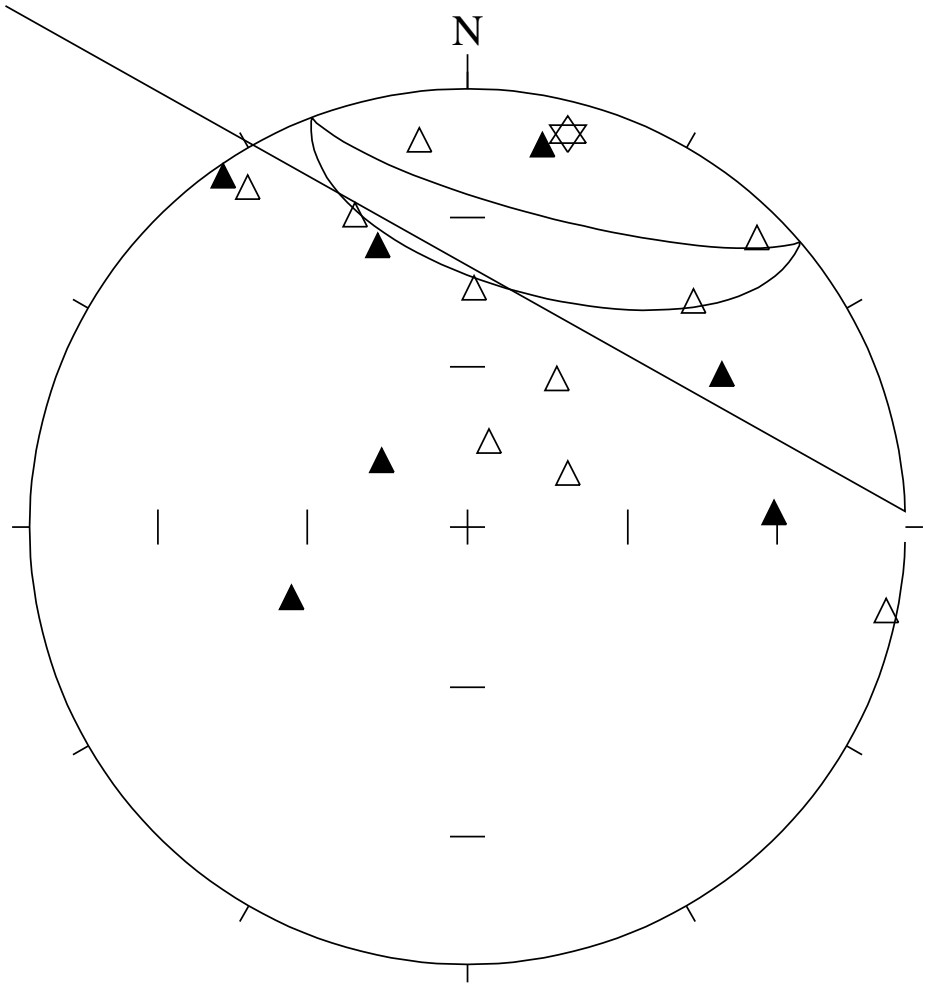


Figure 5.70: Stereoplot showing the NRM of AM82 from Tŷ Mawr. Closed (open) symbols represent positive (negative) inclinations. In the northern hemisphere inclinations should be positive, so any individual directions with negative inclinations are rejected. The mean direction of the data plotted is shown by the grey star and the  $\alpha_{95}$  value shown as a circle.

***Roundhouse E (RHE): AM83, context 92141***

Within roundhouse E the area of burning was not central but offset to the north-western area of the roundhouse and appeared to be focused around a “hearth-stone”. Successive layers of burnt material butted up to a substantial rectangular stone that stood approximately a metre high (figure 5.71). This context was predominately orange clay, with some mottling, and extremely cemented. There were some angular inclusions around the extremities, particularly to the west of the feature and these areas were avoided during sampling.



*Figure 5.71: AM83; Roundhouse E at Tŷ Mawr viewed from southwest showing the sample locations (scale 0.5m).*

The eighteen samples collected from the “hearth” in roundhouse E recorded a magnetic signal, but the strength of the magnetisation was extremely weak (table 5.46 and figure 5.72).

Magnetisation	Mean Dec (°)	Mean Inc (°)	$\alpha_{95}$	N	Demagnetisation field (mT)	No. of discordant samples
NRM	38.2	44.2	24.5	18	-	-

Table 5.46: Summary of the mean NRM for AM83 from Tŷ Mawr; the magnetic directions showed too much scatter to identify a reliable mean direction for archaeomagnetic dating purposes. Data are at site co-ordinates.

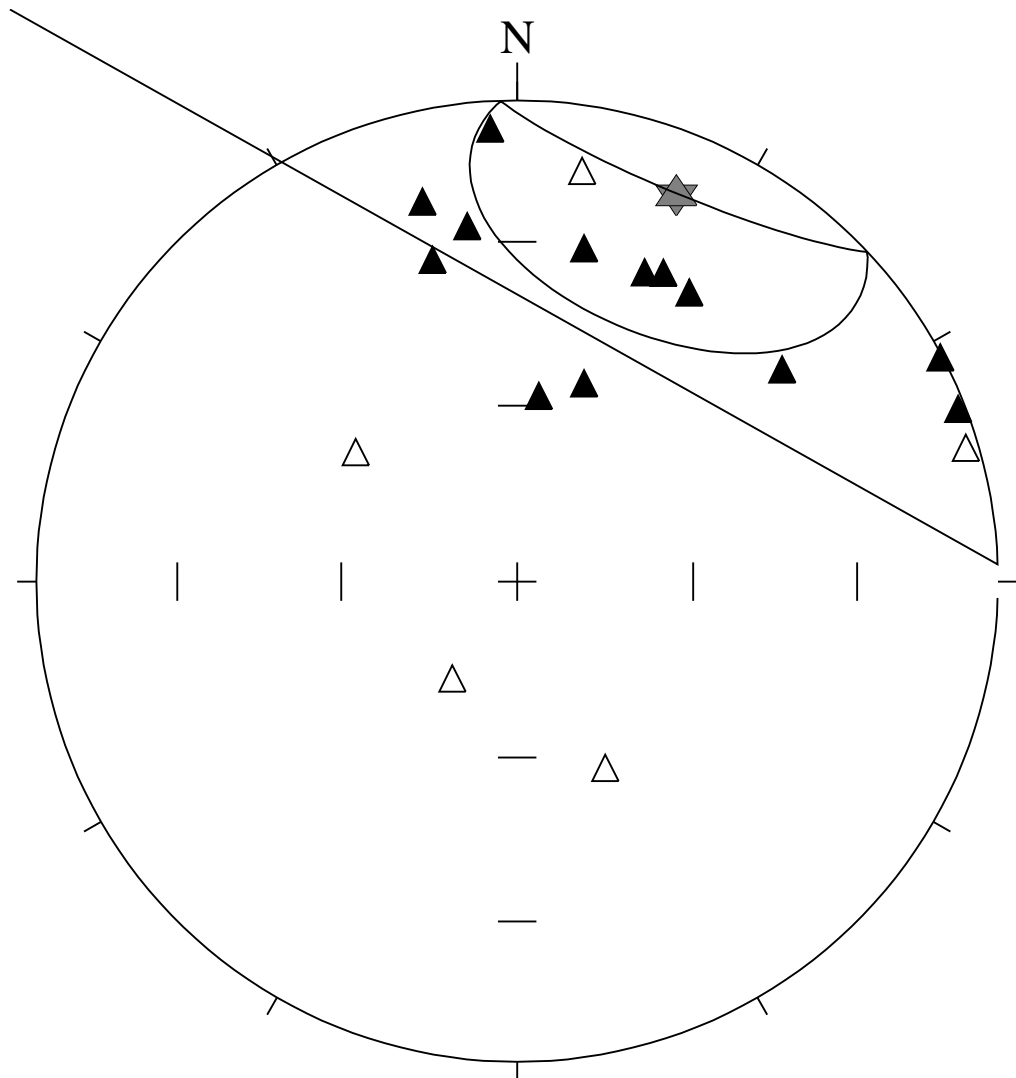


Figure 5.72: Stereoplot showing the NRM of AM83 from Tŷ Mawr. Closed (open) symbols represent positive (negative) inclinations. In the northern hemisphere inclinations should be positive, so any individual directions with negative inclinations are rejected. The mean direction for the data plotted is shown by the grey star and the  $\alpha_{95}$  value shown as a circle.

The levels of intensity displayed by AM81, AM82 and AM83 were approaching the limits of detection for the instruments at the laboratory in Bradford. Given the apparent high level of scatter displayed in all these samples from all these features it was decided not to re-measure with a more sensitive cryogenic magnetometer, or superconducting quantum interface device (SQUID), because it was believed that the additional expense would not yield further information. In summary, the results from AM81, AM82 and AM83 indicate that either the material has not been fired *in situ* to a sufficient temperature, or that the mineralogy of the material does not retain the magnetic signal. Given the circumstantial archaeological evidence for repeated firing events, the most likely explanation is that the material does not contain a sufficient level of the appropriate magnetic minerals to capture the ambient geomagnetic field via TRM, making these features undateable by archaeomagnetism. This phenomenon has also been observed at Porco, Bolivia (Lengyel *et al.* 2011) and may relate to the sample matrix. The circumstances at Tŷ Mawr suggest that low percentages of silt in the sample matrix, and chemical alteration of the mineral species present via weathering processes are possible causes for the loss of the TRM signal (Tarling 1983: 70).

## 5.4 Conclusions

This chapter has outlined the methodology used to sample and process archaeomagnetic samples following established protocols (Tarling 1983; Clark *et al.* 1988; Linford 2006). There were two objectives to undertaking fieldwork to collect more magnetic directions: 1) to collect more data from the Iron Age period for the archaeomagnetic database, and 2) to raise the profile of archaeomagnetic dating within the archaeological community. During the course of this project, it has been possible to obtain a total of 25 new magnetic directions (table 5.47), despite the combined effects of the economic downturn in recent years and the impending Olympic Games in London, which have both resulted in a reduction in both the amount of development/infrastructure work undertaken outside of London and the monies available for research excavations.

Site	Sample Reference	Stable direction	Independent age assessment
Bamburgh Castle	AM130	Yes	No
Birnie	AM87	No	No
Birnie	AM159	No	No
Birnie	AM160	Yes	No
Castlehill	AM70	No	No
Castlehill	AM71	Yes	Yes
Kidlandlee	AM131	Yes	Yes
Market Deeping	AM173	Yes	Yes
Market Deeping	AM174	Yes	No
Mellor	AM134	No	Yes
Poulton-le-Flyde	AM84	No	No
Poulton-le-Flyde	AM85	No	No
Poulton-le-Flyde	AM86	No	No
Sadlers End	AM180	Yes	Yes
Street House	AM132	No	No
Street House	AM133	Yes	No
The Cairns	AM157	Yes	No
The Cairns	AM158	Yes	No
The Cairns	AM163	Yes	No
The Cairns	AM164	Yes	No
The Cairns	AM165	Yes	No
The Cairns	AM175&6	Yes	No
Tŷ Mawr	AM81	No	No
Tŷ Mawr	AM82	No	No
Tŷ Mawr	AM83	No	No

*Table 5.47: The overall success of the fieldwork.*

In order for the field work data to be incorporated into the British archaeomagnetic database it was necessary that each magnetic direction had a precise and reliable independent age estimate associated with it. The financial factors mentioned above have also impacted on the availability of funds for post excavation work, resulting in the stalling of most of the projects after the completion of fieldwork. All of the sites visited were selected because there was reason to believe that there could be some Iron Age occupation. However, without evidence to confirm this assumption or to refine the age range, these magnetic data could only be included with large age estimates of 700BC-AD43, if they were from sites in southern Britain, or 700BC-AD600 if they were from further north (section 2.2). Therefore, most of the new data collected could not currently be included in any future SVC. Only three data points have associated independent age estimates; AM71 (Castlehill) and AM134 (Mellor) both have associated radiocarbon determinations, from material recovered from the hearth feature sampled for archaeomagnetism, and AM131 (Kidlandlee) has chronologically diagnostic artefacts from the same phase. Of the remaining 22 new magnetic directions obtained, only 11 met the level of magnetic precision suitable for archaeomagnetic dating. The remaining samples failed to provide suitable magnetic directions and the main reasons were a combination of the following three factors: 1) lack of magnetic minerals present in the matrix of the material sampled (AM81 and AM83 from Tŷ Mawr); 2) the material sampled had not been heated to a sufficiently high temperatures during use (AM84, AM85 and AM86 from Poulton-le-Flyde) and 3) post depositional disturbance (AM87 and AM157 Birnie; AM132 Street House) or post-excavation weathering of the material sampled (AM70 from Castlehill; AM82 from Tŷ Mawr and AM173 from Market Deeping). So, when added to the data examined in chapter 4, this field and laboratory work takes the total data points collated or collected and examined up to 257.

The second objective was to raise the profile of archaeomagnetism as a viable dating method for archaeological features and was successfully achieved in three ways. Firstly, there was the comprehensive canvassing campaign undertaken

at the beginning of this project that yielded a very positive response. It would appear that many archaeologists are familiar with the term “archaeomagnetic dating”, but are unsure what it dates or how to apply the age estimates from the archaeomagnetic technique. Without this awareness of the types of features that can be dated by archaeomagnetism, as well as the necessity to protect the feature and collect samples soon after it is first excavated, the full potential of archaeomagnetism will not be realised. Secondly, several presentations on the application of archaeomagnetic dating were given during the course of this project. The aim of these talks was to provide information on this dating technique to contemporaries within academia and the commercial sector working in Britain. With this in mind presentations were given at the following conferences: UK Archaeological Sciences, Nottingham BGS (2009); Iron Age Research Student Seminar, Bournemouth University (2009), Scottish Iron Age Matters, Orkney College (2008) and the Yorkshire Archaeological Postgraduate Research Group, Sheffield University (2008). Finally, there is the field work that was undertaken during this project; again each field visit was taken as an opportunity to explain the potential applications of this dating technique to those working in field archaeology.

Chapter 6 will move onto consider another potential source of magnetic data, i.e. lake sediments, before the history and development of archaeomagnetic SVCs are discussed in chapter 7. This penultimate chapter will also provide a summary of the entire British dataset and demonstrate how the adjustments made will improve any future SVCs or global models that utilise the revised dataset.

## **6. An exploration into the potential for incorporating lake sediment sequences into secular variation curves for archaeological applications.**

“It is a poor sort of memory that only works backwards.”

Lewis Carroll, “Alice’s Adventures in Wonderland” 1865

### **6.1 Introduction**

As the overall aim of this research is to characterise the short term variations experienced by the geomagnetic field during the first millennium BC, it was decided that the available lake sediment data should be considered along with data from fired material. Due to the different mechanisms by which these materials record the geomagnetic field (sections 3.6 and 3.7) they have been treated separately, with fired materials dealt with in chapters 4 and 5. In this chapter the primary focus will be on lake sediment data, although other sources of data recorded by detrital remanent magnetisation (DRM) will also be considered. The main question that this chapter will attempt to address is whether the British secular variation curve (SVC) can be composed both of magnetic data recorded by thermoremanent magnetisation (TRM), for example archaeological fired material, and DRM from water-lain sediments. This will be approached by attempting to quantify a selection of issues identified with these datasets, so determining if it is possible and valid to combine magnetic directions from archaeological and geological materials.

Several international research teams are working on analysing the palaeomagnetism recorded in geological material and their data are available via the National Geophysical Data Centre (NGDC), National Oceanic and Atmospheric Administration (NOAA) and the International Association of Geomagnetism and Aeronomy (IAGA). There has been some debate on the suitability of applying magnetic data from lakes to archaeological materials (section 2.5.2), and in some



respects lake sediments present an ideal base for reference curves as they potentially offer a near continuous record of the changes in the geomagnetic field. This possibility was recognised by Clark and co-workers (1988) who adopted this approach for the first archaeomagnetic calibration curve for Britain, pre 1AD. In fact, most of the “Clark curve” that covers the range 1000-100BC is based on a three point running mean of detrended lake data from the British master curve (Clark *et al.* 1988: 664). This master curve (Turner & Thompson 1982) is effectively a composite of the available palaeomagnetic records recovered from sediment cores collected from British lakes. The current SVC (Zananiri *et al.* 2007) excludes lake sediment data, which does not leave many data points covering the first millennium BC. This in turn impacts on the reliability of any archaeomagnetic dates obtained from this period (Donadini *et al.* 2009; Lodge & Holme 2009); therefore it seemed prudent to seriously consider the potential of lake sediment data to “fill in the gaps”.

The main reasoning behind attempting this analysis is timeliness, since this research project has made significant improvements to the precision of the age estimates associated with the magnetic directions from archaeological materials (section 4.7). It is believed that this may enable any differences between these two archives to be identified. This reappraisal has also detected a pronounced gap in the dataset, and suspects that the archaeological record alone may be insufficient to address it (section 4.7.3). The analysis will begin by summarising arguments for and against the inclusion of lake sediment data in the SVC, then detail how the British master curve was constructed and critique previous attempts to date the magnetic signals from lake sediments. The specific problems that will be targeted in this chapter will be outlined, and the procedures chosen to address them will be described. The analyses have been broken down into a series of questions, the particular approach for each stage is outlined and results from each stage are discussed separately, before the overall impact of this approach is considered and some recommendations for future research are made.

### 6.1.1 Lake sequences: a controversial dataset

At the end of section 4.7.3, it was suggested that data from lake sediment sequences could be used to “fill in the gaps” created by the nature of the archaeological record, as they appear to act as continuous recorders of the geomagnetic field. In addition, the sediments from British lakes would cover the entire Holocene period, so contain records of secular variation (SV) dating back to the end of the last Ice Age. A survey of published regional SVCs suggests that no other research groups have utilised magnetic data from lake sequences in their SVCs besides Clark and co-workers (1988). It would appear that the main reasons against including data from lake sequences have included the “lock-in depth” i.e. related to problems of knowing what time delay this represents and any possible smoothing of the magnetic signal (Pavón-Carrasco *et al.* 2011). Previous studies (Yang *et al.* 2009; Saarinen 1998; Barton & Barbetti 1982), have found that the palaeosecular variation (PSV) recorded by lakes is substantially smoothed compared to the signals recorded by archaeological material; leading to the conclusion that making comparisons between archaeological and lacustrine sediments would be problematic. It is argued that these problems are probably related to the challenges involved with applying dating evidence to these sequences.

The basic principle behind the acquisition of a remanent magnetisation in lake sediments is that the Earth’s magnetic field (EMF) imposes a torque on magnetic particles present within the sediment that tends to align particles with the magnetic field (section 3.7). The debates in the literature have tended to focus on the timing of this mechanism, whether it is synchronous with the time of deposition or at some point after deposition (King 1955; Collinson 1965; Løvlie 1974; Verosub 1977; Tucker 1983; deMenocal *et al.* 1990; Tauxe *et al.* 2006; Liu *et al.* 2008) and, if the latter, how long after deposition (Saarinen 1999; Roberts & Winklhofer 2004). The view taken here is that natural sediments tend to floccate (O’Melia 1989; 1998; Katari *et al.* 2000; Katari & Bloxham 2001), so the magnetic minerals that would be influenced by the ambient geomagnetic field are contained within larger aggregates. Therefore the physical explanations given for post depositional

remanent magnetisation (PDRM) would not be dominant, (section 3.7). In brief, the PDRM process allows for the rotation of magnetite grains in pore-spaces within the deposited sediment matrix until, due to de-watering and compaction, they become “locked in”. The depth at which this occurs is referred to as the “lock-in depth”. This is unlikely to occur if the magnetite grains were part of larger aggregates or composite flocs before they settled out of suspension in the water column (Katari & Bloxham 2001). Some researchers suggest that even after settling under gravity some grains are mechanically mobile, so can still reorient post deposition (Collinson 1965). This is seen as creating a “time lag” between the time of deposition and the point at which the ambient field is recorded that is difficult to correct for (Nourgaliev *et al.* 2005). Erroneous age calibration of the sediments (Gallet *et al.* 2002) have also been cited as a cause for the muted record of the actual variations experienced by the geomagnetic field present in lake sediments. It is the opinion here that a similar situation to that identified with archaeological material and addressed in section 4.4 also applies to lake sequences; namely that the issue lies with understanding the taphonomic processes and it is necessary to use that understanding to apply the associated dating evidence.

### **6.1.2 Overview of the British lake data**

Along with the revised and updated British archaeomagnetic dataset (appendix 1), data from the British master curve (Turner & Thompson 1979; Turner & Thompson 1981; 1982) and London observatory data (Malin & Bullard 1981) were used during the analyses in this chapter. The lake data used here were from both the original datasets used to construct the master curve and the detransformed master curve its self. All data were downloaded from the International Association of Geomagnetism and Aeronomy (IAGA) database available at [www.ngdc.noaa.gov/geomag/paleo.shtml](http://www.ngdc.noaa.gov/geomag/paleo.shtml). The British master curve was compiled from cores collected from three British lakes: Windermere (WIND), Loch Lomond (LLDR) and Llyn Geirionydd (GEIR) (figure 6.1). The lakes were chosen due to their geology and bathymetry (Turner & Thompson 1981) and 6m long cores of sediment were collected using pneumatically controlled Mackereth corers (Mackereth 1958).

Several cores were collected from each lake, of which at least three cores underwent magnetic analysis, where natural remanence magnetisation (NRM) direction and susceptibility were measured. This involved the collection of orientated cubic samples with a volume of  $5\text{cm}^3$  at  $2.5\text{cm}$  intervals down the length of the core (Turner & Thompson 1981). This resulted in a total of over 1400 pairs of declination and inclination data from Loch Lomond ( $N=668$ ), Windermere ( $N=359$ ) and Llyn Geirionydd ( $N=392$ ).

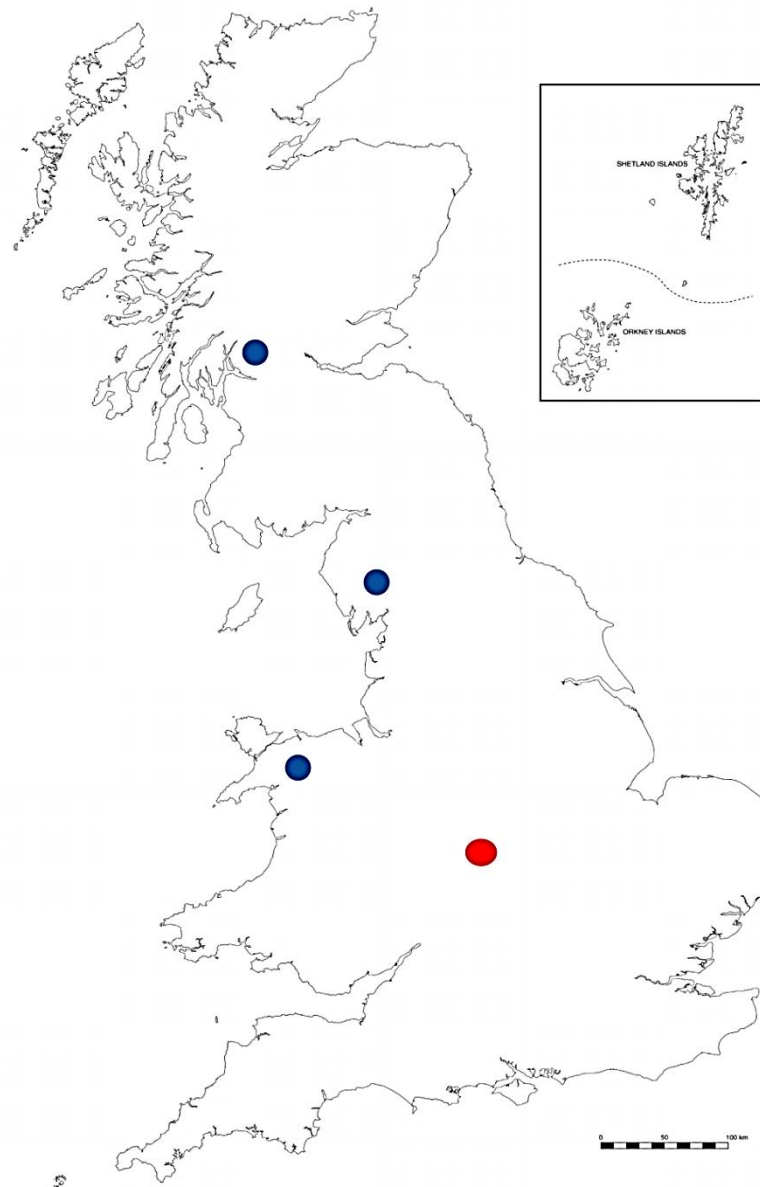


Figure 6.1: Map showing the location of the three lakes: Loch Lomond, Windermere and Llyn Geirionydd, also marked in red is the location of Meriden, ( $\varphi = 52.43^\circ \text{ N}$ ,  $\lambda = 1.62^\circ \text{ W}$ ), to which data were relocated to in some of the analyses performed in this chapter.

Although tests for stability were carried out on the cores, the authors decided that demagnetisation made little overall difference to the NRM directions so utilised the NRM records. Observations on the British lake sediment data by Turner and Thompson (1982) suggested the Loch Lomond and Windermere sediments provided well-grouped, high amplitude patterns of remanence, whereas the Llyn Geirionydd record, whilst following the same general trends, was much more scattered and showed lower amplitude changes. Of these three lakes, they considered the sequence from Loch Lomond to provide the best estimate of the amplitude of secular geomagnetic variation, (figure 6.2). The differences between the records from each of the lakes are a problem that needs to be overcome to combine several lakes into a single master curve (Thompson & Clark 1989; Zillén 2003). Although, it could be argued that these are purely due to differences in the nature of the sediments: porosity, size and shape of the particles and the magnetic carrier present within the matrix (Verosub 1986).

To allow for uncertainties with sedimentation rates, it is general practice to utilise another variable to correlate the sequences from each lake; typically this is susceptibility and was the method applied to the British dataset (Turner & Thompson 1981). Nevertheless, the final stacking of the data from the three lakes was not undertaken objectively, as the data appears to have been combined by visually matching the magnetic features or “swings” observed in the datasets (Turner 1979: 119f); these have been labelled a-i for declination and  $\alpha$ -v for inclination. Then an adjustment to declination was applied by shifting their master curve 13.9° east (Turner & Thompson 1982), as this was the difference between the observed locality and the data from the London observatory. This approach was justified as the cores were not orientated azimuthally during sampling, meaning it was necessary to fix the scale. Therefore the errors shown in the final averaged magnetograms shown in figure 6.3 which suggest that typical errors on inclination are 1° with 3.2° on declination, will not fully represent the variation between the records so apparent in figure 6.2. Furthermore, an important aspect to master curve

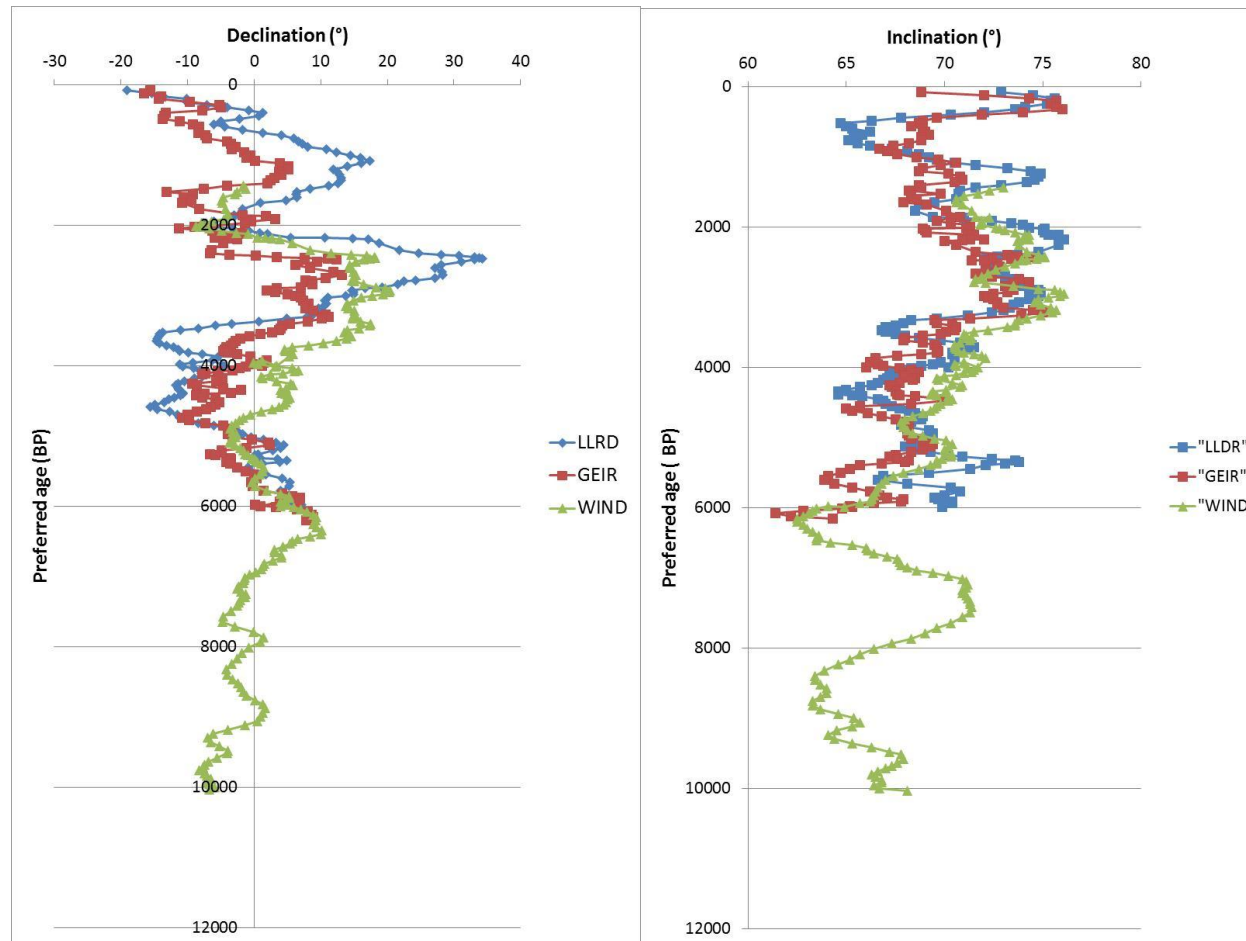


Figure 6.2: Plots of the smoothed lake data used to generate the British master curve (Loch Lomond (LLRD), Llyn Geirionydd (GEIR) and Windermere (WIND)) shown in figure 6.3. These data have been corrected to Meriden, to show the differences between the records of magnetic direction.

construction is the reproducibility between parallel cores from the same locality or within a restricted geographical area (Clark 1983). This essentially provides a check on the quality of palaeomagnetic data. The British master curve available for download from NOAA does not contain any estimate of error on either the magnetic directions from individual cores or the master curve, so it is not possible to fully assess this aspect. There is also no mention of any polar correction for latitudinal variations, although the sites are some distance from each other and the nominal reference latitude and longitude of the master curve is  $\phi = 54.5^\circ \text{ N}$ ,  $\lambda = 3.5^\circ \text{ W}$  which is in the vicinity of Windermere.

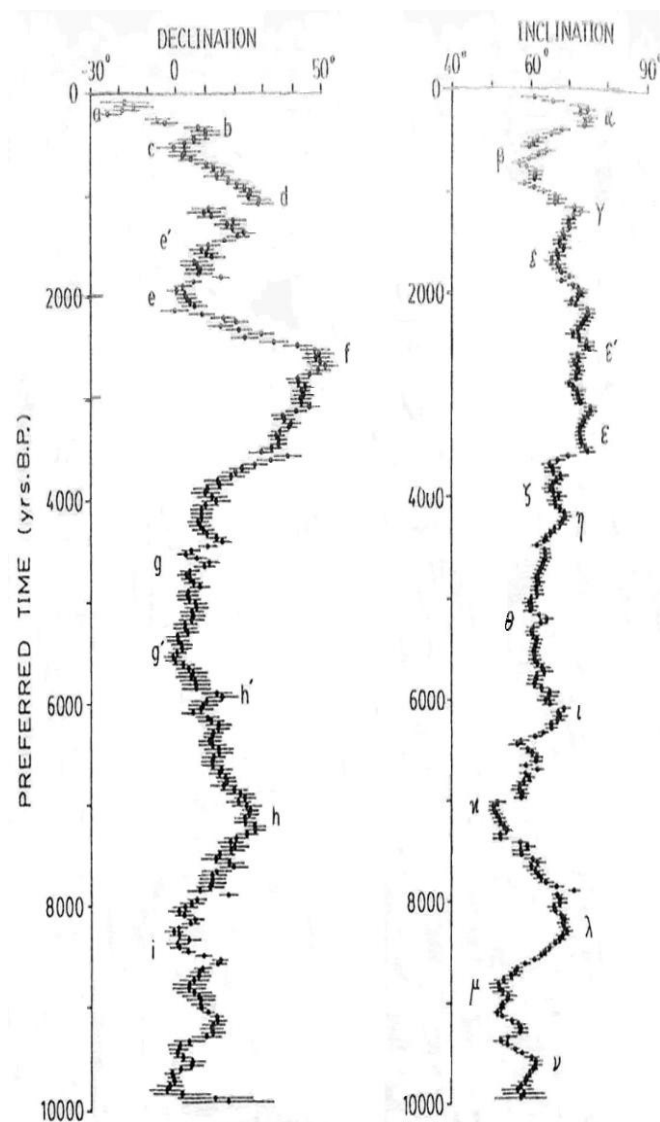


Figure 6.3: The British master curve for palaeomagnetic secular variation obtained by averaging three lake cores (Loch Lomond, Windermere and Llyn Geirionydd) against the “preferred time” at 40 year intervals (Turner & Thompson 1982). © Wiley-Blackwell reproduced with permission.

### 6.1.3 Critique of the dating applied to British lake sediments

An important issue parallel to how the original data were combined and stacked to produce the British master curve, is the reliability of the “preferred time”, (figure 6.3). In fact the question of whether or not to include the magnetic directions from British lake cores rests on this aspect, as it is possible to restack and correlate the original data to provide a new master curve. The British lake master curve was the first attempt to use lake sediment data in this manner, so it became a point for comparison for all subsequent work on magnetic directions from lake sediment data worldwide (Creer *et al.* 1981; Barton & Barbetti 1982; Creer & Tucholka 1982; Thompson *et al.* 1985; Stockhausen 1998; Saarinen 1999; Nourgaliev *et al.* 2003; Snowball *et al.* 2007). This is a position that it currently retains, but this research was now undertaken over thirty years ago (Turner & Thompson 1981) with significant advances made during that time. Of particular relevance are those made in the application of radiocarbon dating to sediments (Bronk Ramsey 2008b), particularly as the reliability of the radiocarbon determinations retrieved from material from all three lakes was questioned at the time (Turner & Thompson 1981). The main reason for this was because there was little agreement with the dates obtained from a previous study (Mackereth 1971).

The samples for radiocarbon determination from the Turner and Thompson (1981) master curve consisted of 20cm blocks of sediment, due to the low organic context of the sediment (Turner 1979: 106), to enable sufficient carbon content for conventional radiocarbon dating from each of the lakes. The sampling strategy was essentially to target specific depths of the cores where predominate “peaks” had been observed in the magnetograms. Therefore the overall date range associated with the British lake data given as “preferred time” appears to have been derived by comparing calibrated radiocarbon determinations closest to features a-i and  $\alpha$ -v identified in the declination and inclination dataset respectively, as shown in figure 6.3. Although each of the individual radiocarbon determinations were considered to be imprecise, as they consisted of substantial sections of the core, Turner decided that enough age estimates were “mutually supporting... on and around particular



magnetic features” to construct a “preferred time” (Turner 1979: 111). The radiocarbon determinations from the other two lakes were found to be “in good agreement with each other, feature for feature, and give a smooth sedimentation rate for each lake” (Turner & Thompson 1981: 713). This “preferred time” was then transferred between cores from within Loch Lomond and within Llyn Geirionydd by visual correlation of the magnetic features and between the Windermere cores via lithological correlations (Turner 1979, chapter 5). This procedure of using “tie points” and assuming a uniform accumulation rate between the tie points is now commonly applied to estimate ages in sets of samples from lakes to ice cores (McMillan *et al.* 2002). Other options, include cross validation to fit the depth-age data, followed by a smoothing cubic spline as applied to the Irish master curve (Thompson & Edwards 1982), or attempting to model the differences between the actual and inferred age and allow for errors due to uncertain tie points and variable accumulation rates (McMillan *et al.* 2002; Stanton *et al.* 2010). Either of these other approaches would have allowed some of the possible issues identified with the accumulation rates between Loch Lomond and Windermere to be examined in detail.

It was decided to test how robust the “preferred time” is by using a recent innovation in the OxCal 4 program, deposition modelling of radiocarbon determinations using Bayesian logic (Bronk Ramsey 2008b). This enables additional information about the depositional processes to be incorporated with the radiocarbon determinations in a more formal manner and provides a framework for assessing cross correlations between different cores in a more rigorous and objective manner. The “P sequence” was applied to the sequence of radiocarbon determinations from Loch Lomond, Windermere and Llyn Geirionydd, as it is the most appropriate model for lake sediments. All the information available on the sedimentation rates and the difference in lithologies down the cores (Turner 1979; Turner & Thompson 1981) was utilised as the prior information. The results suggest that, with the exception of the Windermere sequence, the relative radiocarbon

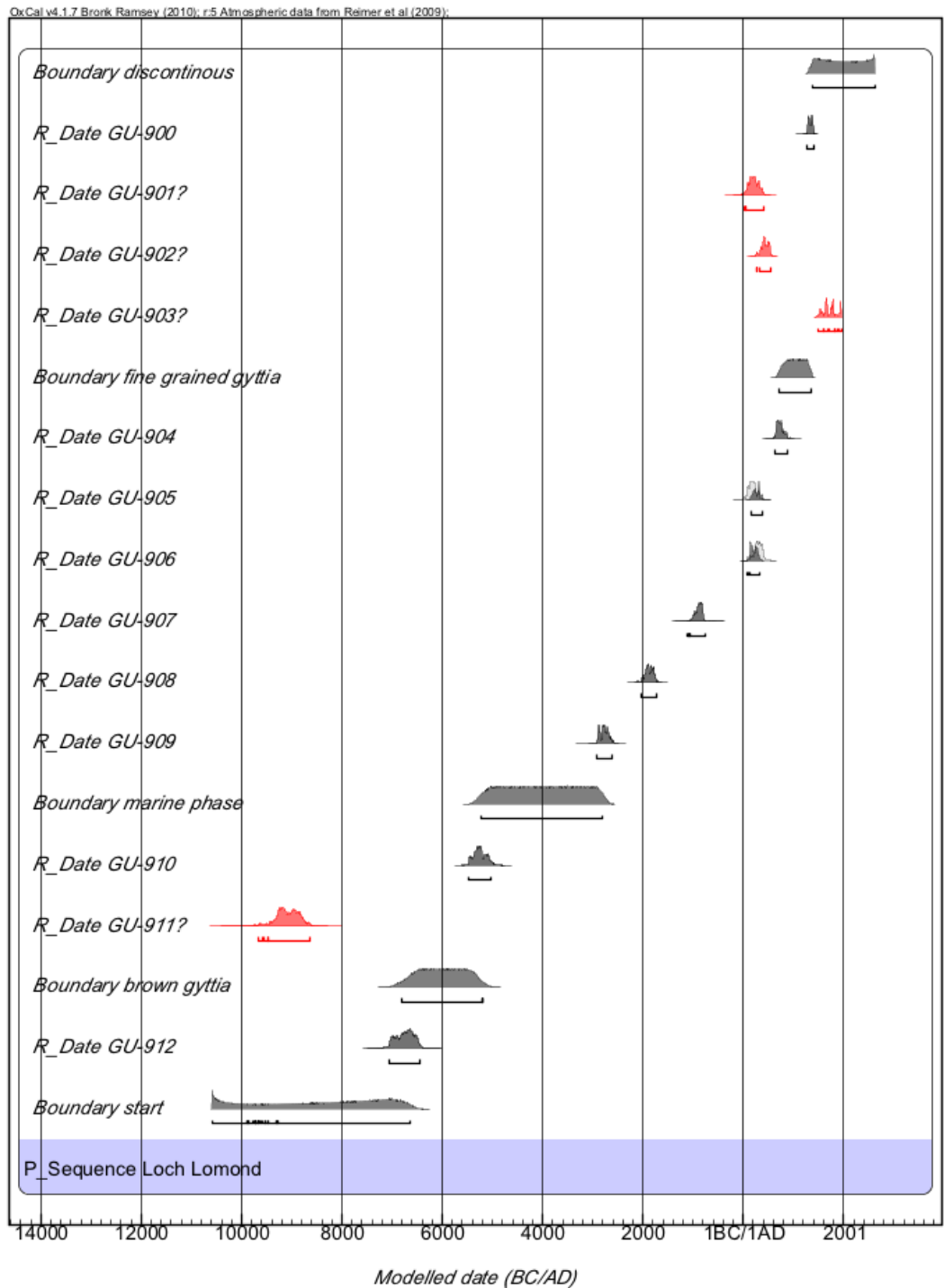


Figure 6.4: A probability distribution for the radiocarbon determinations from Loch Lomond (LLDR):  $A = 77.7$  but zero  $k$  value, where  $A$  is the agreement index and shows how well the prior model agrees with the observations. This set of dates was selected for modelling as they formed the basis of the dating for the British master curve, this plot shows how some radiocarbon determinations do not match their stratigraphic positions, given the quoted sedimentation rates and observed changes in sedimentology. The low value of  $k$  represents the uniform rate of deposition that had been assumed by Turner and Thompson (1981). The distributions highlighted in red were identified as outliers as they did not fit their stratigraphic positions.

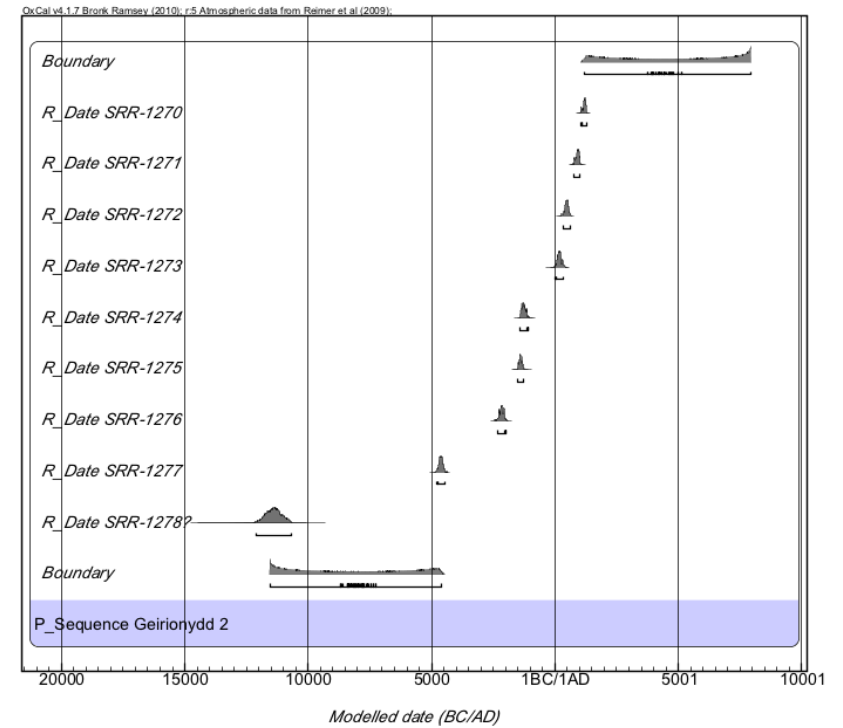
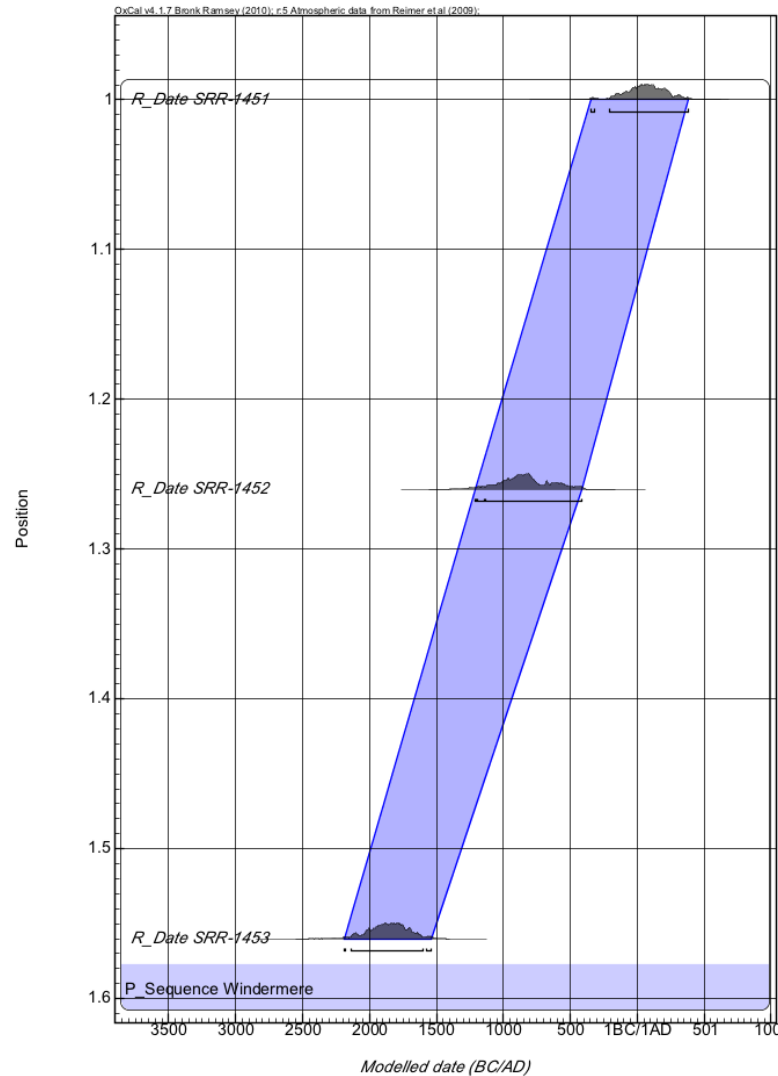


Figure 6.5: A series of probability distributions for the radiocarbon determinations from Windermere WIND1 (left):  $A=99.9$ ; Llyn Geirionydd GEIR2 (top):  $A=102$  but both have zero  $k$  value, see figure 6.4 for explanation. These were selected for modelling as they were two cores utilised to compare the radiocarbon determinations from the features in the record of magnetic directions. Information of the specific model for each lake is provided in appendix 2.

ages may be out of order (figures 6.4 and 6.5). The dating from Windermere consists of only three determinations, so that the observations match their stratigraphic positions is both unsurprising and uninformative. Therefore in this case Bayesian modelling has confirmed initial suspicions regarding the reliability of the dating which forms the basis of the British master curve. The overall agreement for a model of the sedimentation profile of the core from Loch Lomond using OxCal 4.1 (Bronk Ramsey 2008b) was 77.7% but with a zero  $k$  value (figure 6.4). The  $k$  value represents the rate of deposition, where zero represents a uniform rate as this is what had been assumed for the British master curve. This is taken to suggest that the radiocarbon determinations from Loch Lomond that formed the backbone of the “preferred time” and the implicit assumption of a uniform deposition rate are perhaps problematic. For completeness, the probability distributions for the radiocarbon determinations from Windermere WIND1 and Llyn Geirionydd GEIR2 have also been modelled (figure 6.5). Any further interpretations of this model are limited due to the size of the error ranges associated with the individual radiocarbon determinations, which are most likely due to the amount of bulk material sampled to obtain each radiocarbon determination. Essentially, it can be concluded that in this case it was inappropriate to use radiocarbon dating in this manner, i.e. to only date the features identified in the magnetograms (figure 6.3) and use these features as the basis for an age-depth model. It would have been preferable to also sample at regular intervals down the core, as this would allow for better modelling, because this sampling protocol could enable changes in deposition rate to be identified. There are now more robust and objective methods of performing this type of analysis with radiocarbon dates, for example wiggle-matching, which has been applied to a variety of other natural archives (Christen & Litton 1995; Lanci & Lowrie 1997; Blaauw *et al.* 2003; Yeloff *et al.* 2006; Holmes *et al.* 2009). Although this is only useful for radiocarbon determinations obtained via accelerator mass spectrometry (AMS), but age-depth or deposition modelling is another viable option that has recently been applied successfully (Stanton *et al.* 2010).

The final “preferred time” (Turner & Thompson 1981), as allocated to the British master curve, was constructed using observatory data from London, archaeomagnetic data (presumably from the work done at Oxford for the first millennium AD (Aitken & Hawley 1967), although this is unclear) and radiometric dating from predominately Loch Lomond, (figure 6.6). When the sequence of dates from each of the lakes was treated separately it was possible to see that the calibrated Loch Lomond radiocarbon determinations do show some overlap with Turner and Thompson’s “preferred time”. This is probably because Loch Lomond was used to fix the dating of the main magnetic features and the other records were fitted to this record by linear stretching (Turner 1979: 120f). There are two main problems with this approach. Firstly the organic fraction was recovered from 20cm blocks of sediment, which at the estimated sedimentation rate for Loch Lomond ( $0.3\text{mm yr}^{-1}$ ) (Turner & Thompson 1979: 412) represents nearly 700 years of accumulation, if the sedimentation rate was constant, which only further compounds the issue of identifying a potential “time lag”.

Secondly the approach of using the morphology of the palaeomagnetic curve is problematic, as if several records are to be combined it is important to identify where the records differ not just where they match (Clark 1983). Here sequence slotting is a mathematical approach to compare records which lack precise dating but have an internal order where the data sequence is known unambiguously (Thompson & Clark 1989). Previous researchers applied this method to assess the quality of match of palaeomagnetic secular variation both within and between British lakes. They found poor within lake agreement in the records from Loch Lomond and Windermere and the agreement between Windermere and Loch Lomond was borderline (Thompson & Clark 1989: 180 table 1), which led them to summarise that Windermere and Loch Lomond lake sediments were not good recorders of geomagnetic direction. The opinion taken here is that their conclusions may be premature, but they highlight the need for the lake sediment data to undergo a series of objective treatments. In this manner it should be possible to

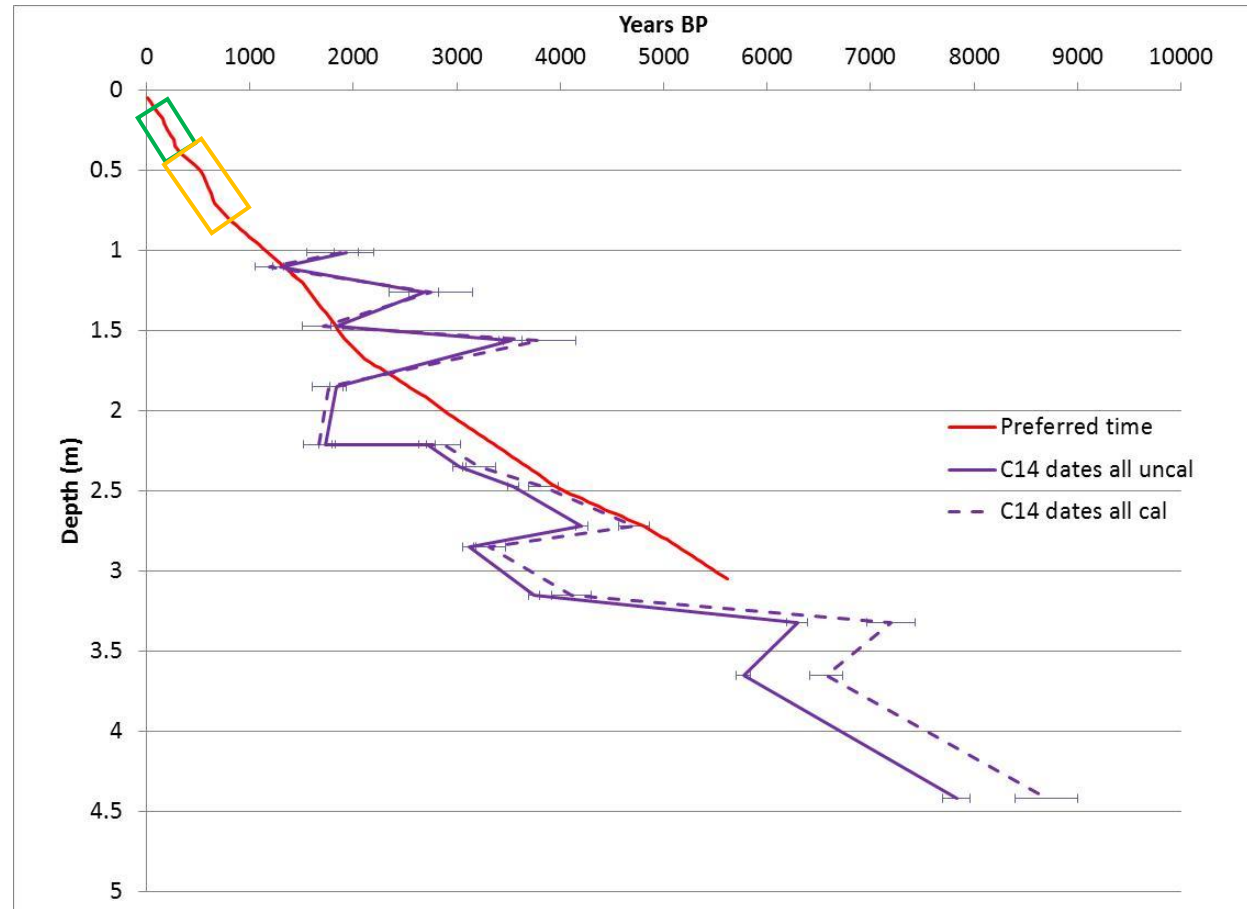


Figure 6.6: Graph showing how the age-depth model constructed for the UK master curve compares to the radiocarbon determinations recovered from the cores. The graph also highlights the section of the model constructed from observatory data (green box), archaeomagnetic data (orange box) and radiocarbon determinations (rest of model) and compares both calibrated and uncalibrated dates BP from the three lakes.

determine whether the sequences from the British lakes arise from a common signal, i.e. reflect actual changes in the geomagnetic field over time.

As British lakes do not contain varves dating cores will be difficult, and it may prove challenging to identify tephra within cores retrieved from British lakes. It is possible that volcanic ash fell on the British mainland during the Holocene period, but it is unlikely to have fallen in sufficient quantities to form visible layers within lake sediments. Nevertheless, tephras have been found in many Holocene period sediments in Britain; especially Scotland (Dugmore 1989; Dugmore *et al.* 1995), in the form of micro or crypto tephras but it would appear that tephras have not been routinely looked for in British lacustrine sediments. However, given the recent eruption events from the Eyjafjallajökull volcano in Iceland during April and May 2010 (Gudmundsson *et al.* 2010) it may be possible to determine, given favourable prevailing winds, the amount of ash fall that could occur over the British mainland and so the likelihood of finding tephra in British lakes. This leaves radiocarbon dating and the application of radiocarbon dating to the current dataset, which will be assessed below. To conclude, this brief survey suggests that until the data from British lakes is stacked in a more objective manner and more robust dating is obtained for the current sediment sequences, any direct comparisons to magnetic directions from fired materials would be misleading. The rest of this chapter will be devoted to testing this hypothesis by interrogating the currently published data to answer a series of research questions.

## **6.2 The research questions**

As the current exclusion of lake data will impact on the reliability of any dates obtained from this period (Zananiri *et al.* 2007; Donadini *et al.* 2009; Lodge & Holme 2009; Pavón-Carrasco *et al.* 2011), it was decided to focus on determining the reliability of the “preferred dates” applied to the British master curve. The temporal precision of the data from material where the recording mechanism is DRM are considered, with a specific focus on lake sediment data. Due to the great

potential that lake sediment sequences can offer, i.e. a near continuous record of secular variation for the entire Holocene, it is important to ensure its inclusion in the SVC is valid. Three critical factors were identified that would require answering satisfactorily and the first of these was fairly fundamental,

1. Are captured directions (DRM or TRM) actually representative of the ambient geomagnetic field?
2. Are the magnetic directions captured by DRM internally consistent?
3. What is the relationship between the observed direction and the age that is assigned to that section of the core?

The latter question may be difficult to address given the method used to construct and date the current British master curve (section 6.1.3). Nevertheless, four different research questions were devised to assess the suitability of lake sediments. These are:

1. How significant is the hypothesised “time-lag” in the palaeomagnetic signal retrieved from lake sequences?
2. How accurate are lake sequences in general as recorders of the contemporary geomagnetic signal?
3. Does a direct comparison between the apparently contemporary magnetic signal recorded by fired archaeological material and water-lain deposits reveal the same direction?
4. How accurate is the TRM mechanism at capturing the contemporary geomagnetic field?

Together these questions hope to addresses the universal issue of whether lake sediment data can be utilised in secular variation curves that are to be predominately employed in dating directions from fired material.

### **6.2.1 The potential for comparisons with other magnetic data**

As mentioned above, a critique of the dating applied to the British master curve suggests it may be problematic. Even so, since the pioneering work of Turner and Thompson (1979), and several other lake sediment sequences obtained across



Europe all appear to show the same distinctive patterning (Stockhausen 1998; Frank *et al.* 2002; Ojala & Saarinen 2002; Snowball & Sandgren 2002; Ojala & Tiljander 2003; Nourgaliev *et al.* 2005; Irurzun *et al.* 2006; Snowball *et al.* 2007). In particular, the magnetic feature marked “f” on the British Master curve; a large westerly change in declination is seen in all records that extend in longitude from Britain to Siberia. There are now other Holocene lake sequences where magnetic directions have been measured (Donadini *et al.* 2009 table 4). To identify whether it was worth including the magnetic directions from the British master curve dataset in the British SVC, these data were compared to the most robustly dated lake sediment sequence with high resolution chronological control in Europe, the FENNOSTACK sequence (Snowball *et al.* 2007). Given that the FENNOSTACK sequence is based on varved sediments and was derived from six independently dated varve sequences which were combined using radiocarbon determinations and tephra isochrons to cross-match the dating of the sequences, it is hoped that this will negate any issues regarding the consistency of the sedimentation rate. Visual comparison of FENNOSTACK to the British master curve suggests that the ages of the most significant features of the sequence are a few hundred years younger in the FENNOSTACK data compared to the British data (Snowball *et al.* 2007: 112, table 3). This could be attributed to the application of radiocarbon dates from bulk sediments for the latter. Comparison of the relative directions from both master curves suggests that these two records do show the same general pattern (figure 6.7). Even with the issues with dating highlighted in section 6.1.3, both master curves appear to have yielded the same general pattern, which is quite surprising.

### **6.2.2 The procedure to examine the data via “snapshots”**

The FENNOSTACK master curve and the British master curve for palaeomagnetism were both interrogated to answer the four questions defined in section 6.2. As the British and Fennoscandian sequences are only separated by around 20° longitude or 1790 km, the effects of “non-dipole transformations” of the geomagnetic field over this region should be relatively small (Thompson 1982). Therefore, if it was assumed that the time-averaged field is a geocentric inclined

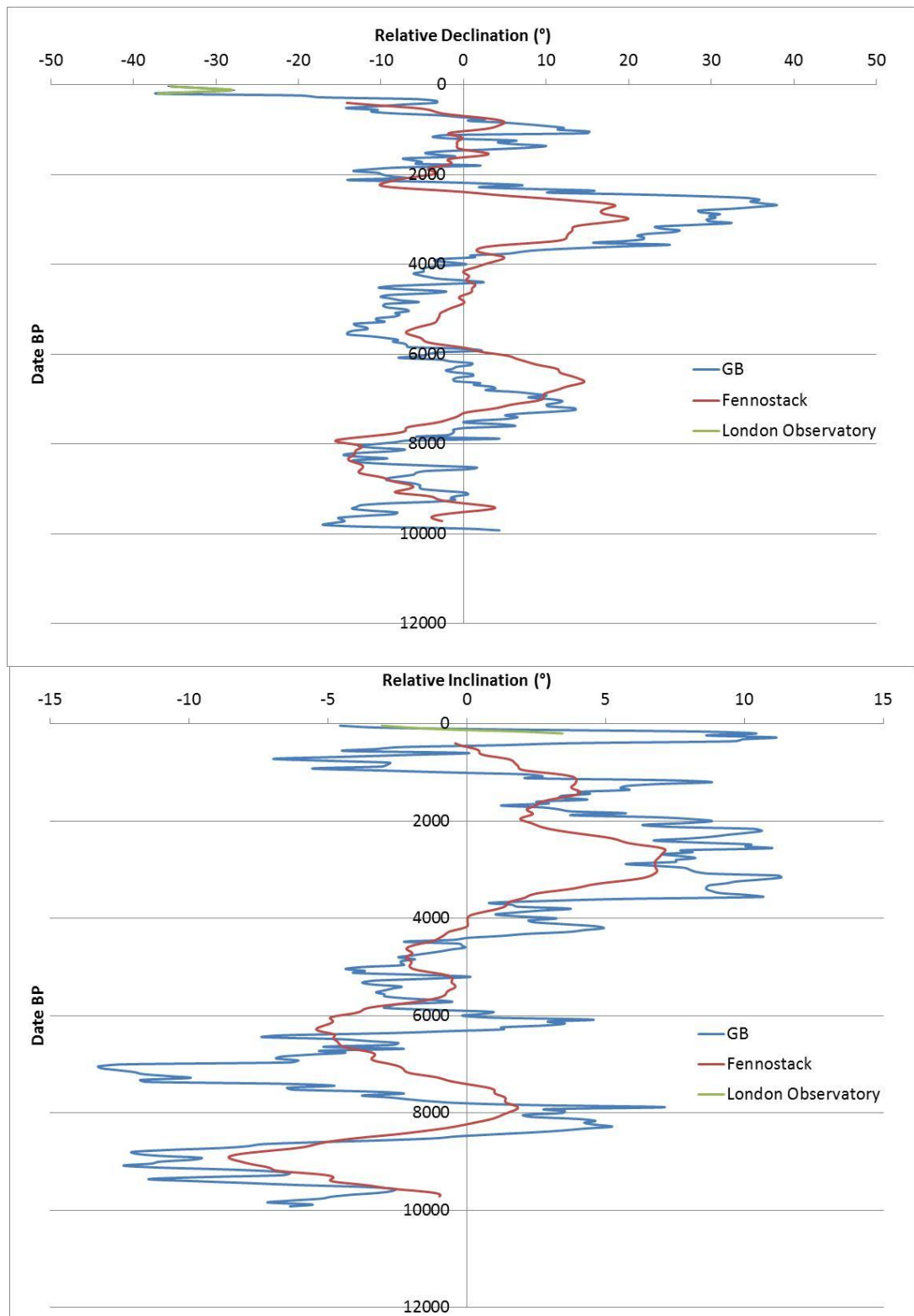


Figure 6.7: Charts showing the relative declination (top) and inclination (bottom) values for the London observatory, British master curve (GB) and FENNOSTACK. Data replotted from Malin & Bullard 1981, Snowball et al. 2007 and Turner & Thompson 1982. A point by point analysis has been performed on the British master curve and FENNOSTACK reduced to Meriden (section 6.4 and appendix 1) confirming that they do not match over the first millennium BC section (3090-10760BP).

axial dipole (Piper & Grant 1989; Merrill & McFadden 2003), it could be possible to compare them directly (Nilsson *et al.* 2010). The British data were used as published, whereas the data for the Fennoscandian sequence, FENNOSTACK (Snowball *et al.* 2007), is available only as relative directions about a zero mean, with a nominal reference latitude and longitude of  $\phi = 61.9^\circ \text{ N}$ ,  $\lambda = 18.7^\circ \text{ E}$ . The data used in the following analyses were generated by applying the mean value from the British lake master curve (Dec =  $12.7^\circ$ , Inc =  $64.1^\circ$ ) to each relative direction from FENNOSTACK for the period 3080-1760BP (data generated are in appendix 1). Where magnetic directions from fired material have been used, only those where either the date of firing was known, i.e. a modern firing, or, for archaeological material, a sample with an independent assessment of date directly related to the material sampled for archaeomagnetic dating, were included.

In order to generate “snapshots” the FENNOSTACK sequence was averaged over a window of a targeted time interval covering ‘n’ samples and these data were utilised to calculate a resultant vector for the periods of interest. These “snapshots” from the FENNOSTACK sequence were then compared to a range of other magnetic directions that, according to their associated dating evidence, were contemporary. It was hoped that this approach may lead the way to gaining deeper insight into whether TRM and DRM data can be combined. The method of calculating the mean direction for each interval, using Fisherian statistics, is outlined in section 3.3. Next, these “snapshots” were compared to a contemporary (according to current dating evidence) direction from a different source (e.g. observatory or archaeological) using the McFadden & McElhinny (1990) test. The application of the test in this manner was inspired by Sternberg’s proposal for calibrating archaeomagnetic dates (Sternberg & McGuire 1990b: 125f) and is routinely employed by some laboratories for this purpose (Gallet *et al.* 2009: 633). All calculations were carried out using Palaeomag-Tools version 4.2 (provided by Mark Hounslow, Lancaster University). When running the McFadden & McElhinny Reversals test (1990), Palaeomag Tools performs three calculations:

- 1) Initially, as the data utilised were from a variety of sources, it was necessary to ensure that they were reliable to use in further statistical analysis. This was done by comparing the values of  $R$  for each average against the respective  $N$  values in Watson's table of critical values of  $R_0$  for a random distribution for  $N$  (as reproduced in Tauxe 2002: 127 table 4.1). This determined whether the mean directions could have arisen by chance at 95% probability.
- 2) Then the precisions were tested to see if they were comparable by performing a test for common Fisher  $k$ . The results from this test, whether Fisher  $k$  is the same or different, determines which mean direction test is performed. The difference between these two tests relates to how the critical angle is calculated.
- 3) Finally the mean directions are compared. This determines whether these means are from the same population, i.e. do in fact record the same magnetic direction or not. The McFadden & McElhinny test (1990) reverses one of the directions and its circle of confidence through  $180^\circ$  and calculates the angle between the two means, the observed angle,  $\gamma_o$ . Then the angle at which the two directions become significantly different at the 95% confidence level, the critical angle,  $\gamma_c$ , is calculated. If the observed angle is greater than the critical angle, then the mean directions are more dispersed than is to be expected, i.e. they are significantly different. McFadden and McElhinny (1990) formalised the results by classifying the results: "A" if  $\gamma_c < 5^\circ$ ; "B"  $\gamma_c < 10^\circ$ ; "C"  $\gamma_c < 20^\circ$  and "indeterminate" if  $\gamma_c > 20^\circ$ .

The output from Palaeomag Tools provides the results from the test for common Fisher  $k$ , the critical and observed angles and their classification. The rest of this chapter will present each of the four research questions before providing some suggestions for further research.

### **6.3 Part one: observatory data versus lake data**

Question 1: How significant is the hypothesised "time-lag" in the palaeomagnetic signal retrieved from lake sequences?

Turner and Thompson (1982) stated that the most recent remanence directions from Loch Lomond closely follow the London observatory data, but this appears to be a visual comparison that has not been quantified. As observatory data are historical measurements, a comparison to the most recent section of the master curve should remove any of the potential errors due to the radiocarbon dating strategy highlighted in section 6.1.3. The London observatory data up to AD1975 comprises 238 direct historical observations of the geomagnetic field (Malin & Bullard 1981) with observations from the last 35 years taken from the IAGA database. Although observatory records extend back to AD1570, both declination and inclination were not recorded until AD1723. Furthermore, as the top section of the lake cores were potentially subject to disturbance during the sampling process, only measurements of direction between AD1750 and AD1910 from British data were compared.

### **6.3.1 Method for part one**

A comparison of the data from the London observatory data (Malin & Bullard 1981) was done using the McFadden & McElhinny (1990) test on magnetic directions from the British master curve (Turner & Thompson 1982). This comparison was done using the Reversal test in Palaeomag Tools (section 6.2.2). If at 95% confidence the observed angle ( $\gamma_o$ ) is less than the critical angle ( $\gamma_c$ ), the difference between the means is due to within sample variation, so they are recording the same direction. If  $\gamma_o > \gamma_c$  then they are significantly different.

### **6.3.2 Results for part one**

The results are presented in table 6.1 and figure 6.8, where the former shows the actual data. They clearly demonstrate that any comparison between lake sediments and observatory records are not straightforward, as the directions from the last eighty years do not show any agreement.

Date (AD)	Turner & Thompson 1982			Malin & Bullard 1981			$H_0$ is true at 95% confidence
	Declination	Inclination	$\alpha_{95}$	Declination	Inclination	$\alpha_{95}$	
1910	337.5	59.3	3.6	343.9	67.7	0.5	N
1870	341.8	60.8	3.6	339.2	68.8	0.5	N
1830	344.9	65.5	3.6	335.2	70.3	0.5	N
1790	341.0	72.2	1.8	335.9	72.7	0.5	Y
1750	336.0	74.3	1.8	342.5	74.2	0.5	Y

Table 6.1: The results from comparing the magnetic directions from the British Master curve and observatory data as published, error values for British master curve were measured off figure 1 in Turner and Thompson (1982) who had calculated them using a three-point running mean. For London observatory data 0.5° was used to account for possible instrumental errors (Zananiri et al 2007).

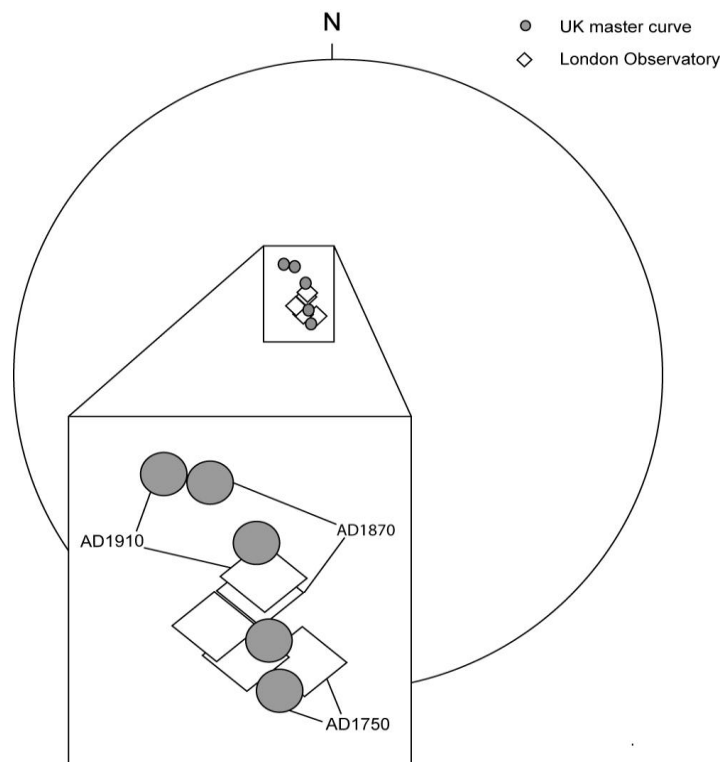


Figure 6.8: Stereoplot showing the five pairs of absolute values utilised in the comparison between the UK master curve and data from the London observatory. There is a discrepancy between the most recent pairs of data.

The same results are obtained if all the data are relocated to Meriden (appendix 1). There are five possible explanations for these results:

- The “time lag” is a real phenomenon (Løvlie 1974) and has a significant impact on the recorded direction, these results suggest around 100 years for British lakes;
- The shallowing of the inclination value due to the “bedding error” (King 1955) has a significant impact;
- The “preferred time” (Turner & Thompson 1981) as determined for the British Master curve is flawed;
- Errors were introduced during the sampling process as the top section of the core was disturbed, so it is possible the core was misorientated;
- There is evidence of significantly increased (300%) sediment flux affecting Lake Brassenthwaite during the past 150 years (Hatfield & Maher 2009). Windermere, which was used as the base for the magnetic directions in the master curve, is located in the same vicinity, therefore could have also been affected by anthropogenic catchment disturbance (Hatfield *et al.* 2008).

### **6.3.3 Conclusions for part one**

Turner and Thompson (1982) used the London observatory record to calculate a correction to the entire sequence by shifting it 13.9° east, to fix the scale, but then it does raise the question of why the first 80 years do not match within the errors of measurement. Evidence from varved sediments suggest that there may be lag of at least 100 years (Saarinen 1999) but others workers give considerably higher estimates (Björck *et al.* 1998), which these results appear to support. However, it is suggested here that the problem lies with the radiocarbon sampling strategy and the assumption of a constant sedimentation rate (section 6.1.3). Particularly, as there is evidence to suggest an increase in lake sediment flux over the past 150 years in the English Lake District due to increasingly intensive land use and revetment construction which has reduced sediment storage (Hatfield & Maher 2009). These recent findings would impact on the estimated sedimentation

rates and are a possible cause for the discrepancy apparent in table 6.1 but would have been unknown to Turner and Thompson (1981). Regardless, the question of how to deal with this issue remains and the results so far suggest that the situation is more complex than a systematic time lag and if anything these problems have arisen due to the assumptions relating to the age depth relationships of the sampled material.

#### **6.4 Part two: the British lake sequence during the first millennium BC**

Question 2: How accurate are lake sequences in general as recorders of the contemporary geomagnetic signal?

This question is examining the much debated topic of “lock-in depth” (Tauxe *et al.* 2006) but from a different angle, as here the emphasis rests much more on the importance of the relationship between dating applied to the cores and the event of interest, the recording of the ambient field. This section will look at intra sample variation by comparing the published data from individual British lakes. Research on varved lake sediments (Zillén *et al.* 2003), found that apparently acceptable single entity radiocarbon determinations from lake sediments could be erroneous, requiring the application of several independent dating methods. This implies that it may be difficult to directly transpose the British data to a regional reference curve, and three potential sources of error can be identified. Firstly, there is the perpetual issue of relating the event dated by radiocarbon with the event that one wishes to date. The presence of residual or “old” carbon inwash is often quoted as the most likely explanation (Turner & Thompson 1981); this is amplified by problems associated with the unknown secular variations of  $^{14}\text{C}$  in the atmosphere, and the analytical errors associated with radiocarbon determinations (Pilcher 1991). Secondly, there is a similar problem for magnetic directions, with regards to the event of interest, as there is still some debate relating to the time at which the magnetic carriers within lake sediments become locked in position, so recording the contemporary geomagnetic field (Katari & Bloxham 2001; Roberts & Winklhofer 2004; Tauxe *et al.* 2006). Some laboratory studies on deep-sea sediments suggest



that the magnetism is recorded post-deposition and that the time lag is fairly pronounced (Løvlie 1974; Lund & Keigwin 1994; Kent & Schneider 1995; Channell *et al.* 2004), and studies on modern analogues (Batt 1999) appear to agree with these results. Work on compiling a palaeosecular variation master curve for Fennoscandia has examined annually laminated sediments (Saarinen 1998; Saarinen 1999; Zillén 2003) and suggests that for minerogenic lake sediments the “lock-in time” for the magnetic carriers, particularly if they are biogenic, is less than 100 years whereas other research have suggested up to 200 years (Barton & Barbetti 1982).

The third potential source of error is differences in sedimentation rates, both from year to year and between different lakes. Research on Russian lakes suggests that in non-varved sediments combining the signal from different lakes is problematic (Nourgaliev *et al.* 2005). Therefore, this incomplete knowledge of the age-depth relationship of a lake core is a major limitation and the associated uncertainties have not been fully accounted for (McMillan *et al.* 2002). Twenty centimetres of core sediment was required from each of the British lakes in order to obtain 1g of organic carbon for each radiocarbon determination. Depending on the sedimentation rate, which was assumed to be  $0.03\text{mm yr}^{-1}$  (Turner & Thompson 1981), this could represent several centuries of accumulation. A comparison of AMS  $^{14}\text{C}$  dating of bulk sediment with terrestrial macrofossils from Swedish lakes suggests that bulk dates can be at least several hundred years too old (Björck *et al.* 1998). The Swedish case study did have some marine input, but even if the marine reservoir effect was not an issue, as with the British lakes, the results still demonstrate that dating different fractions from the sediment can produce dates differing by a century. If this is the case with the British lakes, and if the geomagnetic field was changing rapidly during this period as suggested by several lake sediment records across northern Europe (Turner & Thompson 1981; Stockhausen 1998; Ojala & Saarinen 2002; Snowball & Sandgren 2002; Zillén 2003; Nourgaliev *et al.* 2005), a difference of even a decade could be sufficient to cause a statistically significant difference in the magnetic direction recorded by the sediments in different lake sequences, never mind 600 years.

In order to determine whether each of the independently dated core sequences from British lakes recorded the same direction at a particular point in time, data from three British lakes sampled to create the British lake master curve, Windermere (WIND), Loch Lomond (LLDR) and Llyn Geirionydd (GEIR), were compared. It should be possible to address this question by examining the dating applied to the British master curve by focusing on the first millennium BC, peak “f” figure 6.3, as this was a major magnetic feature identified in all cores (Turner 1979: 115 table 5.3). Ten cores from three British lakes were combined to create the British lake master curve, and 15 radiocarbon determinations from three different cores (one core from each lake). Only the six radiocarbon determinations that relate to the first millennium BC, where peak “f” is located (table 6.2), were examined. Of these three radiocarbon determinations, GU-905 SRR-1451 and SRR-1273 showed considerable overlap. Therefore the section of the core these radiocarbon determinations were collected from were examined to see if they recorded the same direction.

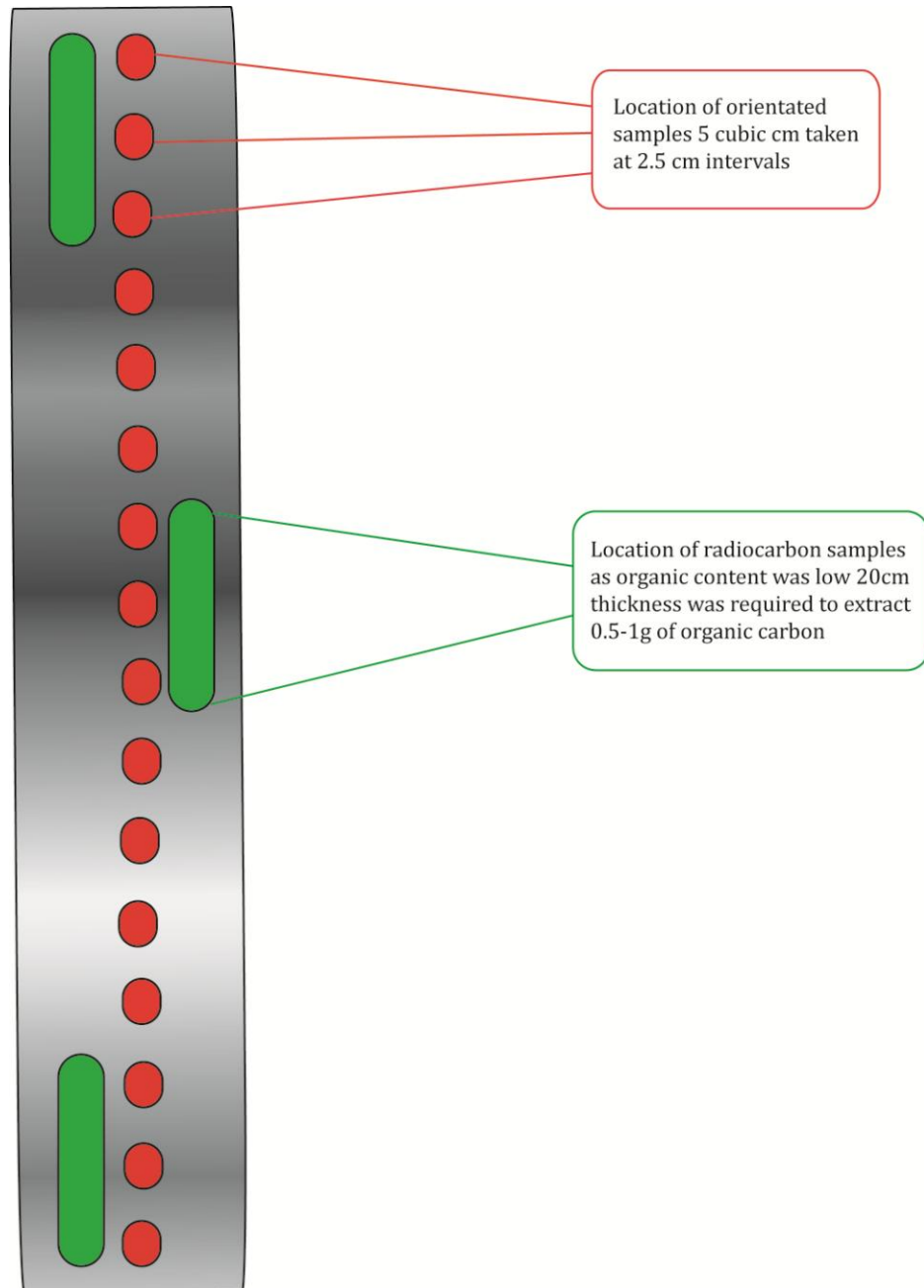
Lake	Core	<sup>14</sup> C lab reference	<sup>14</sup> C determination BP
Loch Lomond	LLDR1	GU-904	1294±69
Loch Lomond	LLDR1	GU-905	1838±59
Loch Lomond	LLDR1	GU-907	2712±78
Llyn Geirionydd	GEIR2	SRR-1273	1835±65
Windermere	WIND1	SRR-1451	1930±120
Windermere	WIND1	SRR-1452	2680±140

*Table 6.2: The radiocarbon determinations from the British master curve that relate to the first millennium BC, the dates highlighted in red show remarkable similarity so the associated magnetic directions were compared to determine if they recorded the same event.*

#### 6.4.1 Method for part two

As 20cm blocks of sediment were sampled in order to obtain the radiocarbon determinations, (Turner 1979: 106) the magnetic directions that were

obtained over the same depth range were combined to produce a mean direction, illustrated in figure 6.9 (data in appendix 1). This provided a mean direction that corresponded to the depth of sediment dated by the radiocarbon determination. These mean directions were then compared to each other using the McFadden & McElhinny test (1990), to see if they were all recording the same direction at the same time interval.



*Figure 6.9: A schematic to illustrate the relationship between the two sampling strategies undertaken on the British lake cores to obtain the magnetic directions and radiocarbon samples.*

## 6.4.2 Results for part two

The mean directions for the section of the sediment that provided the radiocarbon determinations are displayed in table 6.3. These suggest that these lakes are not recording the same direction over the same time period, as defined by the radiocarbon determinations, so are not reliable indicators of geomagnetic secular variation. It is suggested that these results only demonstrate that a section from two different lakes, which have been given a similar date in radiocarbon years BP, have recorded different magnetic directions. Given the sampling method used (figure 6.9); it is more likely that the age estimates are incorrect. Furthermore obtaining a match using this test is only possible if the cores were aligned properly, and these results suggest that this was not the case.

Core	Mean Declination	Mean Inclination	$\alpha$ 95	N	$^{14}\text{C}$ Lab code	$^{14}\text{C}$ determination (BP)	$H_0$ is true at 95% confidence
LLDR1	353.9	56.1	2.9	6	GU-905	1838 $\pm$ 59	N
WIND1	350.2	66.9	2.0	8	SRR-1451	1930 $\pm$ 120	N
GEIR2	309.4	67.6	2.6	8	SRR-1273	1835 $\pm$ 65	N

*Table 6.3: The results from combining the individual directional vectors that correspond to the radiocarbon determinations GU-905 from Loch Lomond and SSR-1273 from Llyn Geirionydd, corrected to Meriden ( $\varphi = 52.43^\circ \text{ N}$ ,  $\lambda = 1.62^\circ \text{ W}$ ). The magnetic directions that corresponded to the depth of material sampled for radiocarbon, see figure 6.9, were used to generate these mean values, data are available in appendix 1.*

## 6.4.5 Conclusions for part two

This presents a curious situation, separate lakes appear to be recording the same magnetic changes over time, even when there is little confidence in the dating associated with the lake cores. In the absence of single entity radiocarbon determinations, it was necessary to compare mean directions from 20cm thicknesses of the cores. The results shown in table 6.3 suggest that the ability of the sediments from Loch Lomond, Windermere and Llyn Geirionydd to accurately record the pattern of geomagnetic secular variation differ, and previously this has been attributed to differences in sedimentology. It is more likely that the

application of dating evidence is the cause. This is before the potential biases in radiocarbon dating are considered, which of course could be compounded by the impact of hill inwash (Turner & Thompson 1979), and difficulties comparing  $^{14}\text{C}$  sequences from different lakes (Björck *et al.* 1987). The approach used here, calculating a mean direction over 20cm depth, may also have masked any rapid changes in the geomagnetic field that occurred when that depth of sediment was deposited. The cumulative effect of these issues implies that sediments from different lakes, which produce a similar radiocarbon determination may not actually relate to the same point in time. With regards to lock-in depth, the view taken here is that many of the errors that other workers have attributed to lock-in depth may actually originate in issues relating to assumptions made regarding age depth relationships and taphonomic issues, mainly the difficulties relating the event dated by radiocarbon (the cessation of uptake of radiogenic carbon from the atmosphere) to the target event of interest (when the sediment settled and the ambient geomagnetic field was recorded).

### **6.5 Part three: archaeological data versus lake data**

Question 3: Does a direct comparison between apparently contemporary magnetic signals recorded by fired archaeological material and water-lain deposits reveal the same direction?

The third question will attempt to address an issue fundamental to the selection of data sources for the construction of a regional SVC. This is testing whether TRM and DRM are capable of capturing the same ambient field and maintaining this archive over archaeological time scales, i.e. the last 12 000 years. This will be approached in two different ways as there are two potential sources of DRM data that could be included in a regional SVC: lake cores and archaeological samples from wells, ditches etc. The DRM data from archaeological material will be dealt with first, by comparing pairs of TRM and DRM directions both recovered from archaeological material that have been dated to the same period. Here the re-evaluation carried out in section 4.4 enabled suitable pairs of data to be identified.

Next a selection of directions from archaeological fired material will be compared to “snapshots” from water-lain sediments that have been dated to the same period to see if they are significantly different. Although issues have been identified with the dating assigned to master curves and the lake sequences, the following analysis could show whether the currently available lake data could be used to construct a regional SVC. However, the more chronologically secure FENNOSTACK dataset may be able to investigate the more subtle point relating to the relationship between TRM and DRM mechanisms; essentially whether any magnetic direction that is not TRM should be used to construct a SVC. It was felt that the best approach would be to use the dataset with the most reliable dating, FENNOSTACK, and that reducing the magnetic directions to a single location may counter any potential non-dipole affects.

#### **6.5.1 Method for part three**

From the data collected in chapter 4, there are currently thirteen magnetic directions that were recorded by DRM and relate to the first millennium BC. These are from ten sites, Bigbury Camp; Felday hillfort; Hascombe hillfort; Holmbury Camp; Keay’s Lane; Little Bay; Moor Hall Farm; Mucking; Thanet (N=3) and Yarnton. For two of these sites, Bigbury Camp and Hascombe, each have two sets of directions available for the same target time range. One was recorded by heating (TRM) as the samples were collected from a hearth and the other by deposition (DRM) as the samples were collected from the bottom of a ditch. This meant that only two pairs of directions were available for the first part of this analysis. With regards to the second part, in order to apply the “snapshot” approach the initial difficulty was to identify magnetic directions from archaeological material that had both been independently dated to the first millennium then a magnetic direction for the same date range to had to be calculated from the FENNOSTACK sequence. The results from applying the procedure outlined in section 4.4 meant that average age estimates applied to archaeomagnetic directions from the first millennium BC were now more precise, the modal age range had been reduced from 750 years to 100 years. A total of seventeen sites provided thirty magnetic directions which had

been independently dated to the first millennium BC, with age error estimates of under  $\pm 150$  years. These are Beeston Castle; Bigbury Camp; Bury Wood Camp; City Farm; Cowbit; Felday hillfort; Ferrybridge; Guiting Power; Gwithian; Hascombe; High Rocks; Holmbury hillfort; Kingsdale; Maiden Castle (N=2); Methley (N=2); Mine Howe and Old Scatness (N=12) and they covered the target time span of 1530BC to AD65, all magnetic direction were reduced to Meriden.

The mean from the British lake master curve was applied to the FENNOSTACK relative magnetic data over the target time span of 1530BC to AD65, which were then reduced to Meriden. A single direction representative of the same time interval as the archaeological direction from the FENNOSTACK dataset was obtained by identifying the declination and inclination values that related to the target age range, as set by the archaeological information. A mean direction was calculated for the target interval (figure 6.10). The comparison was done using the McFadden and McElhinny (1990) test on these 32 pairs of observations of the geomagnetic field as derived from archaeological material and the FENNOSTACK dataset relocated to Meriden (appendix 1). The hypotheses being tested were -  $H_0$ : the samples have the same mean direction and  $H_1$ : the samples have different mean directions. If at 95% confidence the observed angle ( $\gamma_o$ ) is less than the critical angle ( $\gamma_c$ ), the difference between the means is due to within sample variation, so they are recording the same direction. If  $\gamma_o > \gamma_c$  then they are significantly different.

### **6.5.2 Results for part three**

The results are presented in table 6.4 and clearly demonstrate that any comparisons between lake sediments and archaeological data are challenging. Overall, comparison with FENNOSTACK data resulted in a match occurring in 31% of cases. In principle this supports the idea of lake records being substantially smoothed, and does not represent the presence of actual differences in the recording process.

Fenno lake interpolated data at Meriden Kingsdale						
Date	Dec	Inc	North (l)	East (m)	Down (n)	$l^2 + m^2 + n^2$
-1392.38	25.02	66.72	0.358191	0.16718	0.918559	1
-1402.38	24.99	66.64	0.359382	0.167483	0.918038	1
-1412.38	24.95	66.56	0.360716	0.167851	0.917448	1
-1422.39	24.93	66.47	0.362099	0.168299	0.91682	1
-1432.39	24.91	66.37	0.363535	0.168821	0.916156	1
-1442.39	24.90	66.27	0.365099	0.16944	0.915419	1
-1452.39	24.87	66.14	0.366918	0.170122	0.914565	1
-1462.4	24.85	66.01	0.368942	0.170828	0.913619	1
-1472.4	24.80	65.87	0.371083	0.171468	0.912632	1
-1482.4	24.72	65.72	0.373443	0.171929	0.911581	1
-1492.4	24.60	65.57	0.375979	0.172148	0.910497	1
-1502.41	24.42	65.43	0.378564	0.171864	0.909479	1
-1512.41	24.16	65.30	0.381246	0.171019	0.908518	1
-1522.41	23.83	65.18	0.384017	0.169595	0.907617	1
-1532.41	23.39	65.07	0.386872	0.167345	0.906822	1
			5.556086	2.545389	13.69777	
Number =	15					
Sum x =	5.5561					
Sum y =	2.5454					
Sum z =	13.6978					
R =	14.9993					
x bar =	0.3704					
y bar =	0.1697					
z bar =	0.9132					
Mean Dec	24.6138					
Mean Inc	65.9555					
Alpha95 =	0.2767					

Figure 6.10: Showing the data and calculation steps utilised to produce the mean direction from FENNOSTACK used for comparison with mean direction from archaeological material from Kingsdale; estimated age range 1460BC±70.



Date range	Site	Mean Declination	Mean Inclination	$\alpha$ 95	N	H <sub>0</sub> is true at 95% confidence
1460BC±70*	Kingsdale	25.1	72.9	2.8	17	N
	Fenno	24.6	66.0	0.4	11	
1020BC ±100*	Gwithian	12.4	66.3	2.6	8	N
	Fenno	30.9	69.3	0.2	15	
435BC±75	Beeston Castle	9.3	71.7	2.0	8	N
	Fenno	11.4	67.9	0.8	12	
300BC±100	Ferrybridge	13.4	66.1	3.7	7	Y
	Fenno	4.4	66.6	0.6	15	
200BC±100	Methley	355.7	69.5	2.6	11	N
	Fenno	4.0	65.5	0.4	15	
200BC±100	Methley	340.2	63.6	13.3	5	Y
	Fenno	4.0	65.5	0.4	15	
180BC±130*	Old Scatness AM61	356.9	67.1	2.4	22	Y
	Fenno	4.6	65.4	0.5	19	
175BC±75	City Farm	357.5	72.7	3.1	16	N
	Fenno	4.1	65.3	0.4	11	
150BC±50	Bury Wood Camp	349.8	66.1	4.3	7	N
	Fenno	4.7	65.2	0.3	8	
150BC±50	Maiden Castle	359.0	70.0	0.7	15	N
	Fenno	4.7	65.2	0.3	8	
140BC±125*	Old Scatness AM60	353.4	68.8	3.3	7	N
	Fenno	5.4	65.1	0.5	18	
125BC±75	Holmbury Camp	350.0	65.8	3.0	5	N
	Fenno	5.7	65.0	0.4	12	
115BC±60*	Cowbit	2.0	69.3	7.3	9	Y
	Fenno	6.2	64.9	0.4	10	
continued						

Date range	Site	Mean Declination	Mean Inclination	$\alpha$ 95	N	H <sub>0</sub> is true at 95% confidence
105BC±85*	Old Scatness AM29	358.5	67.0	3.1	10	Y
	Fenno	6.4	64.9	0.5	13	
105BC±85*	Old Scatness AM38	358.8	64.5	4.6	15	Y
	Fenno	6.4	64.9	0.5	13	
100BC±100	High Rocks	14.4	55.3	3.3	7	N
	Fenno	6.4	64.9	0.5	15	
90BC±85*	Bigberry Camp (TRM)	5.6	67.1	9.1	12	Y
	Fenno	6.9	64.8	6.4	13	
90BC±85*	Bigbury Camp (DRM)	2.3	71.9	2.1	8	N
	Fenno	6.9	64.8	0.4	13	
80BC±60*	Old Scatness AM47	354.1	66.9	2.0	11	N
	Fenno	7.2	64.8	0.4	10	
55BC±110*	Old Scatness AM35	15.6	55.0	7.1	9	N
	Fenno	7.6	64.7	0.3	15	
50BC±100*	Guiting Power	350.8	70.7	2.6	5	N
	Fenno	7.6	64.7	0.3	14	
50BC±50	Maiden Castle	340.4	68.3	6.0	11	N
	Fenno	8.1	64.6	0.3	8	
40BC±130*	Old Scatness AM53	349.7	67.8	4.9	10	N
	Fenno	7.3	64.8	0.3	19	
40BC±130*	Old Scatness AM58	357.9	69.3	2.9	12	N
	Fenno	7.3	64.8	0.3	19	
35BC±55*	Old Scatness AM40B	358.3	60.7	5.0	9	Y
	Fenno	8.5	64.6	0.2	9	
continued						

Date range	Site	Mean Declination	Mean Inclination	$\alpha$ 95	N	H <sub>0</sub> is true at 95% confidence
35BC±55*	Old Scatness AM40B	358.3	60.7	5.0	9	Y
	Fenno	8.5	64.6	0.2	9	
35BC±55*	Old Scatness AM46	349.8	68.6	4.9	6	N
	Fenno	8.5	64.6	0.2	9	
15BC±50*	Hascombe (TRM)	351.1	66.3	3.4	21	N
	Fenno	8.6	64.5	0.1	9	
15BC±50	Hascombe (DRM)	351.8	67.1	5.8	22	Y
	Fenno	8.6	64.5	0.1	9	
15BC±85	Felday hillfort	0.3	67.0	3.1	5	N
	Fenno	8.2	64.6	0.2	13	
15BC±90*	Old Scatness AM22	359.95	64.6	2.3	10	N
	Fenno	8.2	64.6	0.2	13	
15BC±90*	Old Scatness AM23	356.3	68.2	4.0	9	N
	Fenno	8.2	64.6	0.2	14	
AD30±35	Mine Howe MH2	351.7	71.7	5.2	12	Y
	Fenno	8.8	64.5	0.1	6	

Table 6.4: The results from combining the individual directional vectors for the magnetic directions from selected archaeological sites and the FENNOSTACK master curve (Snowball et al. 2007) using the mean direction from Turner and Thompson (1981), corrected to Meriden ( $\varphi = 52.43^\circ$  N,  $\lambda = 1.62^\circ$  W) to provide absolute directions. Dates with an asterisk represents confidence about the archaeological date range assigned (ranks A and B), no asterisk represents doubtful age estimate (ranks C and D, see table 4.4).

The comparison between the TRM and DRM directions also yielded some interesting results. When compared to each other (table 6.5), the results for each pair of TRM and DRM directions suggest that they were recording the same direction. This implies that allocating the same date range to both directions is not

Date range	Site	Mean Dec	Mean Inc	$\alpha$ 95	N	H <sub>0</sub> is true at 95% confidence
15BC±50*	Hascombe (TRM)	351.1	66.3	3.4	21	Y
	Hascombe (DRM)	351.8	67.1	5.8	22	
90BC±85*	Bigbury Camp (TRM)	5.6	67.1	9.1	12	Y
	Bigbury Camp (DRM)	2.3	71.9	2.1	8	

*Table 6.5: The results from combining the individual directional vectors for the magnetic directions, from selected archaeological sites, with directions recorded by both DRM and TRM. Dates with an asterisk represents confidence about the archaeological date range assigned (ranks A and B), no asterisk represents doubtful age estimate (ranks C and D, see table 4.4).*

unreasonable. However, when the pairs of TRM and DRM data were compared to FENNOSTACK it becomes more complicated (table 6.4). At Bigbury Camp, the TRM signal matched FENNOSTACK whereas the DRM signal did not. At Hascombe the reverse was seen as the TRM signal did not match FENNOSTACK but the DRM signal did. It was hoped that these cases studies would be able to illustrate whether the two mechanisms for capturing the ambient geomagnetic were significantly different. If anything, it was expected that the DRM signal would match FENNOSTACK and the TRM signal would not. Although archaeological dating of the directions from archaeological material is still imperfect, and whilst reasonable for these directions, cannot be ruled out as a potential source of error. Furthermore, FENNOSTACK is composed of stacked cores from six different locations and the resultant data stack was smoothed with a running time window of 150 years (section 6.2.1). Therefore it could be argued that comparing to a Fisher mean from a single site (the archaeological data) could not provide a realistic comparison. Yet if lake sediment data were to be incorporated into the British SVC using RenCurve, it is most likely that the combined and smoothed record would be utilised rather than raw data from individual cores. At this point it is postulated that the difficulty

remains with the lake data, whether this is due to issues with dating or obscuring of the signal through data processing.

As a final point of interest, Turner and Thompson (1981, 1982) never specified the source of the archaeomagnetic dating they utilised to refine their “preferred time”. Given the publication date of 1982, it could be assumed that the work of Aitken and Hawley (1967) would have been utilised, therefore the period 200BC-1BC is of particular interest as this period contains three magnetic directions that originate from their (1967) research. These are from City Farm, Bury Wood Camp and High Rocks. None of these sites matched the FENNOSTACK dataset (table 6.4), so it was decided to also compare them to the British lake master curve, just out of curiosity (table 6.6). Surprisingly, City Farm and High Rocks both matched, which suggested that these data could have been utilised in the construction of the “preferred time”, whereas Bury Wood Camp did not match.

Date range	Site	Mean Dec	Mean Inc	$\alpha$ 95	N	H <sub>0</sub> is true at 95% confidence
150BC±50	Bury Wood Camp	349.8	66.1	4.3	7	Y
	British master	3.4	65.9	1.4	11	
175BC±75	City Farm	357.5	72.7	3.1	16	Y
	British master	4.9	68.7	2.3	16	
100BC±100	High Rocks	14.4	55.3	3.3	7	N
	British master	3.3	65.7	0.7	21	

*Table 6.6: The results from combining the individual directional vectors for the magnetic directions, from selected archaeological sites, and the British master curve (Turner & Thompson 1982), corrected to Meriden ( $\varphi = 52.43^\circ$  N,  $\lambda = 1.62^\circ$  W). Dates with an asterisk represents confidence about the archaeological date range assigned (ranks A and B), no asterisk represents doubtful age estimate (ranks C and D, see table 4.4).*

### 6.5.3 Conclusions for part three

Given the problems with a direct comparison between archaeological and lacustrine magnetic data (Verosub 1977; Batt 1999; Nourgaliev *et al.* 2005), it is unsurprising that the results from the simple statistical analyses carried out here gave inconclusive results. It was felt necessary to attempt this comparison, given the improvements made to the temporal quality of the archaeological dataset, as this had previously been stated as a limiting factor (Thompson 1982). The result of this analysis reveals that whilst lake sequences (as represented by FENNOSTACK) and British archaeological dataset are different, they do not appear to be systematically so. This is taken to imply that there is no lock-in depth problem, and that the results which do not match can be explained by the high rate of change experienced by the geomagnetic field over the target time period and the masking effects of the smoothing done to the FENNOSTACK data. Therefore, the lack of matches in the earliest sections of the target period could be contributed to a combination of the rapid change in geomagnetic direction and the lack of precision in the pairs of data point, particularly the dating evidence.

### 6.6 Part four: observatory data versus modern firings

Question 4: How accurate is the TRM mechanism at capturing the contemporary geomagnetic field?

Finally, this question aims to test the implicit assumption in archaeomagnetic dating, that certain physical processes can cause a specific group of minerals to capture an accurate record of the contemporary magnetic field. This was achieved by comparing modern firing events to observatory data. In both cases the dating information is historical and date ranges are given to a single calendar year, therefore removing any issues regarding the precision of the dating applied to the magnetic directions. The modern firings used are from a mixture of experimental archaeology and commercial firings. This approach should also check the reliability of the direction recorded by TRM in heated features. The mechanism of TRM was derived from a series of laboratory experiments carried out by Theiller

(1938) and his conclusions form the elementary assumptions underlying any research using archaeomagnetism of baked sediments. Furthermore, as sections 6.3 to 6.5 suggest that currently published lake sediment data should not be included in a regional SVC, the magnetic directions utilised to construct a SVC will come solely from archaeological deposits. It is therefore prudent to derive some measure of how well these mechanisms work outside laboratory conditions.

#### **6.6.1 Method for part four**

The magnetic directions obtained from a variety of different features that had been recently heated or were last fired at a known date were collated. These were then compared to observatory data from the same date, using the method outlined in section 6.2.2. In an effort to use the most suitable case studies for this comparison, the case studies selected were from two groups of studies. Those conducted to investigate the impact of variations of remanence magnetisation across a feature (Weaver 1961; Hoyer 1982; Catanzariti *et al.* 2008a), and those to compare sampling methodologies (Trapanese 2007; Trapanese *et al.* 2008). Therefore the results from each feature will meet current guidelines, which recommend that characteristic magnetic directions are calculated from at least 16 specimens or 8 samples showing a stable signal and have been collected from evenly distributed sampling sites across the feature (Linford 2006). Furthermore, all the features had been heated to well above the Curie temperature for the principal remanence carrying minerals, magnetite and haematite, so it is possible to assume that the majority of magnetic minerals present would have been sufficiently thermally disordered to be influenced by the ambient geomagnetic field on cooling. Some of the examples are reconstructions (Boxworth, Clearwater and Boston), and these experiments recorded sufficient details to enable comparison of the ability of clay structures to record the ambient geomagnetic field via TRM. A potential limitation with regards to the reconstructions is that they were only heated once so the heat may not have penetrated the entire structure. Nevertheless, if the duration of the heating event was several hours, it is believed that a single use will not present a problem (Weaver 1961). Also, it is not known definitively whether or

not kilns and furnaces in prehistory (particularly pre Roman) were single use. The other examples are industrial or domestic heated features with a known historical date of last use (Gams Valley, Bernalda and Yuste). These features will have been subjected to repeating heating events, so should highlight if the number of heating events create any significant differences. A final point worth emphasising is that none of the modern features selected would have been subjected to the diagenetic processes associated with the incorporation of material into the archaeological record, so potentially represent a “best case scenario”. All the features were still *in situ*, with minimum weathering and bioturbation, thus removing some of the sources of error that plagues the collection of archaeological features. However, as there are still a number of potential sources of error that could be introduced during the collection, processing and measurement of the fired features (Gough 1967; Eighmy 1990; Trapanese *et al.* 2008), it was decided to use the McFadden & McElhinny test (1990) to determine if the observatory data fell within the error ranges of the characteristic magnetic directions determined for each feature, rather than looking for an exact match.

#### **6.6.2 Results for part four**

A summary of all the magnetic directions are provided in table 6.7. When the errors associated with the characteristic remanence are considered, the observatory data lies comfortably within the 95% cone of confidence for the mean direction for half of the examples selected here. This does not necessarily demonstrate that TRM does not capture the geomagnetic field, as this is a small sample, so not very representative. However, it is consistent with the results from Old Scatness, which only achieved a 54% success rate. The excavations at this site took place over a decade with an archaeomagnetist present on site every season to identify and collect samples as suitable features were uncovered. Of the 67 features that were sampled, only 36 provided archaeomagnetic directions suitable for dating.



Country	Site	Longitude	Latitude	Feature	Date of firing	Mean Dec	Mean Inc	$\alpha$ 95	N	Source of observatory data	Within observatory errors	Reference
UK	Clearwater*	51.79N	2.53W	Replica Iron Age furnace	Feb 2005	357.7	64.1	3.72	12	NGDC	Y	Trapanese 2007
UK	Boxworth	52.04N	0.003W	Replica sunken kiln	June 2005	23.9	63.6	4.82	8	NGDC	N	Trapanese 2007
UK	Boston I	52.98N	0.02W	Replica Romano-British kiln	July 1960	5.7	68.1	1.6	16	NGDC	N	Weaver 1961
UK	Boston II	52.98N	0.02W	Replica Romano-British kiln	June 1961	350.1	67.4	1.07	40	NGDC	Y	Weaver 1962
Italy	Bernalda	40.39N	16.69E	Modern kiln	1960	0.0	53.3	0.9	45	NGDC	N	Hoye 1982
Austria	Gams Valley	47.29N	15.27E	Barbecue fireplace	August 2005	14.7	63.8	4.0	6	NGDC	Y	Trapanese <i>et al.</i> 2008
Spain	Yuste#	40.6N	5.75E	Pottery kiln	1959	345.7	60.6	2.9	18	NGDC	N	Catanzariti <i>et al.</i> 2008

Table 6.7: A summary of previous attempts to date modern features via archaeomagnetic dating, \*the author took 35 samples from three levels in the furnace and treated them separately. For the purposes of comparison the 30 most stable measurements were combined to produce an overall magnetic direction for the feature. # Several different methods of calculating the mean direction were applied, the figures quoted here were calculated using Great Circle Analysis (McFadden & McElhinny 1988) of all the samples. As actual dates are not known and it is not recorded how long the feature took to cool, the observatory values for Clearwater, Boxworth, Gams Valley and Boston are an average value for the month that the feature was last heated. For the other examples the value quoted is an average for the year. NGDC is the National Geophysical Data Centre [www.ngdc.noaa.gov/geomag](http://www.ngdc.noaa.gov/geomag).

### 6.6.3 Conclusions for part four

In light of the findings presented in section 6.6.2, the comparison with lake sediments and archaeological DRM provided very similar results to those between modern firing events and observatory data. There are, however, several aspects to TRM magnetic data that require consideration along with the results from the “snapshot” analysis.

- The size of the  $\alpha_{95}$  value, if it is  $> 5^\circ$  this suggests that they are not precise, i.e. there is a lot of scatter or there are few samples;
- The intensity of the magnetisation, if it is low this suggests that either the magnetic signal is very weak or that insufficient magnetic minerals were present within the material to provide a reliable record of the contemporary geomagnetic field;
- Outside of laboratory conditions naturally occurring materials are unlikely to accurately capture the ambient geomagnetic field. In sediments the inaccuracies will probably be compounded by the tendency of water-borne sediments to floccate;
- The relative concentration of magnetic minerals and the proportion of haematite can affect the stability of the magnetic signal and the degree of viscous overprinting, the latter requires that the magnetic signal is cleaned;
- The volume of material sampled, this is typically required to be at least  $10\text{cm}^3$ .

In light of these potential problems, it was necessary to screen the data to maximise the precision with which the magnetic directions are measured. The details of the factors that can affect the reliability of the magnetic data from the case studies are presented in table 6.8. It would appear the most important factor is that the intensity of the magnetic signal is over  $10 \times 10^{-3} \text{ Am}^{-1}$ , followed by the collection method. These extremely limited comparisons demonstrate that in order to produce reliable results it is necessary to consider other factors, but these can be controlled during sample collection and processing (Collinson 1983; Eighmy 1990). Due to the very small number of case studies ( $n = 6$ ), these conclusions are not

definitive but it is possible to suggest some guidelines. If the specimens collected from a feature have: an adequate volume of material, above 8cm<sup>3</sup>; the measured intensity is typically above  $\sim 0.5 \times 10^{-6} \text{ Am}^{-1}$  for consolidated material (higher if unconsolidated) and the  $\alpha_{95}$  value is below  $\sim 6^\circ$  then it is more likely the ambient field will be represented within the 95% confidence interval of the characteristic remanence determined for the sample. This supports the necessity for ranking the magnetic data (section 4.3.2, table 4.2).

Site	Agree with observatory data	Collection method	Cleaning method	Average intensity (mAm <sup>-1</sup> )	Rank
Clearwater	Y	Button	AF	46.5	4
Boxworth	N	Plaster	AF	6.3	4
Boston I	N	Button	TD	952.9	5
Boston II	Y	Button	TD	1186.9	5
Bernalda	N	Cores	AF	0.5	5
Gams Valley	Y	Tubes	AF	13	2
Yuste	N	Cores	TD	3.77	5

*Table 6.8: Details of the other factors that can affect the reliability of magnetic data, AF- alternating frequency; TD – thermal demagnetisation, see section 5.2.4 for more details; Rank, see section 4.3.2 for more details.*

These comments are consistent with observations made by previous workers (for example, Lange & Murphy 1990) and agree with those from another study which attempted to undertake some archaeomagnetic “quality control” (Catanzariti *et al.* 2008a). These researchers found that even when there is a complex NRM history the actual field may still be captured but will provide directions with large dispersions. They also recommend a hierarchical approach to statistical treatment similar to that proposed by Lanos and co-workers (2005). From the results of this survey it is suggested that all the magnetic data in the current British database should be ranked according to their reliability and this issue is

addressed separately in section 4.3 and section 5.2. Furthermore current thinking in this field is that full vector data should be used to develop future SVC's (Schnepp *et al.* in prep) and when constructing them, a weighting system should be employed that allows for the five aspects highlighted here to be taken into account (Schnepp *et al.* 2009). Beyond the benefit of another check on the reliability of archaeomagnetic data, the inclusion of intensity data will enable the construction of more accurate and better constrained SVCs.

## 6.7 Discussion and summary

The main tenet of this thesis has been based on the premise that understanding the mode of acquisition of an archived magnetic signal is critical, as it can have a significant impact on the validity of the application of those data; particularly with respect to the construction of SVCs. The main question that was addressed in this chapter was whether it is possible to incorporate published magnetic data from British lake sediment sequences into a SVC that will predominately be used to calibrate magnetic directions from fired archaeological materials. In this chapter four different aspects were identified as important factors to decide whether magnetic directional data from lake sediments should be included in a reference curve. These are separate to the precision of the individual data points and were:

- that the captured directions are representative of the ambient geomagnetic field;
- that all the magnetic directions are internally consistent, i.e. that they are all recording geomagnetic field at the same point in time;
- assessment of the relationship between the captured geomagnetic direction and the date that has been assigned to the direction;
- how accurately can we realistically date the series of events represented by the recorded magnetic direction?

Previous research into the construction of reference curves (for example: Aitken & Weaver 1962; Aitken & Hawley 1966; Clark *et al.* 1988; Batt 1997), has shown how archaeomagnetic data meet the first two or three of these criteria. Essentially it has been demonstrated that the directions recorded by features heated at a known time match, within tolerable errors, observatory records (Harold 1960a; Hoyer 1982 and section 6.6.2). Furthermore, by only utilising archaeomagnetic directions which contain more than 8 samples and an associated error estimate less than 5° ensures that the magnetic directions are internally consistent (Clark *et al.* 1988; Sternberg 1997). Therefore the relationship between the TRM direction and the archaeological date should be straightforward (Thellier 1938; Aitken 1958). By applying the McFadden & McElhinny Reversals test (1990), it has been possible to quantify some aspects of the magnetism recorded by lacustrine sediments and compare them objectively to archaeological material. From the results of these analyses it is possible to attempt to address the last two points and it has been found that the age-depth relationship in cores is currently poorly defined, as our knowledge of it is incomplete. This in turn impacts on our ability to date any point in the continuous sequence of magnetic data represented by lake sediments. Therefore although magnetic data from lake sequence currently provide a general pattern of secular variation, the specific age/dating detail necessary to enable these data to be used in an archaeomagnetic SVC cannot currently be retrieved from published datasets.

*1. How significant is the hypothesised “time-lag” in the palaeomagnetic signal retrieved from lake sequences?*

This question aimed to avoid the plethora of issues related to using radiocarbon dating by using historical dates. The work here has been interpreted to suggest that there is no “time-lag” as hypothesised from laboratory experiments (Løvlie 1974; Barton & Barbetti 1982). It is postulated that many of the errors that other workers have attributed to lock-in depth actually originate in issues relating to assumptions made regarding age-depth relationships and difficulties relating the event dated by radiocarbon to the target event of interest, i.e. when the ambient

geomagnetic field was recorded. This difference will prove difficult to accurately quantify with sediment records other than varved sequences. With sediment sequences from British lakes, it is not feasible to assume that sediment rates were constant over time within a lake, as has been proved for Bassenthwaite (Hatfield & Maher 2009). The variation observed was due to human activities in the vicinity, so is likely to apply to all British lakes. This is particularly significant for studies focusing on the first millennium BC, as it is believed that the geomagnetic field was changing rapidly. It is proposed that this lack of understanding of the age-depth relationships is the most likely cause of the muted signal from lake sediment sequences that have been identified (Donadini *et al.* 2009). This observation suggests that although the currently available magnetic directions from lake sediments may be suitable for use in global models covering long timespans, they do not currently provide the resolution necessary to examine short time scale changes, which is necessary for the application of SVC's to archaeomagnetic dating.

2. *How accurate are lake sequences in general as recorders of the contemporary geomagnetic signal?*

This analysis found it difficult to identify broadly contemporary events in all the British lakes in order to combine the records with any confidence. Unfortunately there are no isochrons such as tephra layers in the lake sediment records that relate to the first millennium BC, therefore although we appear to have a reliable record of geomagnetic secular variation from at least two British lakes (Windermere and Loch Lomond) there is currently no method to anchor them chronologically. It would appear that the difficulty lies in the problematic nature of applying radiocarbon dating to lake sediments. Additionally, obtaining reliable absolute directional values from these archives, so that they can be cross checked with directions from archaeological materials, may prove challenging. It is believed that the British lake master curve would benefit from a renovation, where it is recreated from the raw data using more objective methods to create a newer version with an error envelop that represents the true nature of the data used to create it. Then there may be scope for combining this revised master curve with a

SVC derived solely with material from archaeological sediments to create an “über SVC”.

3. *Does a direct comparison between apparently contemporary magnetic signal recorded by fired archaeological material and water lain deposits reveal the same direction?*

The analysis carried out here gave inconclusive results, but it is felt that it was necessary to attempt given that the archaeological dataset now contains archaeomagnetic data recovered from water-lain deposits. The direct comparison of water-lain sediments and archaeological fired material undertaken has demonstrated that when both are collected from archaeological sediments they do record the same direction at the same point in time. Yet when directions from apparently contemporary lake sediment and archaeological sediments are compared they do not consistently match. It appears that the source of the difference is in the more rapidly changing declination value. As previously suggested (Gallet *et al.* 2002) any difference in inclination is much less significant than the issues with declination and that these probably relate to the sampling procedure. At this time it is not possible to quantify a general correction factor that could be applied to lake sequences due to a lack of confidence in the age-depth model utilised to date the British lake sediment sequence. Furthermore, the application of a correction factor would be arbitrary and could introduce systematic errors. It would be better to re-sample British lakes and adopt the sampling procedure utilised by Katari *et al.* (2000), where the sediment-water interface was preserved during sampling. Also the application of multi-proxy approaches to the problem of dating lake sediment sequences may be a way forward to address the issue of the age-depth relationship (Creer & Morris 1996; Schmidt *et al.* 2002; Blundell & Barber 2005; Peyron *et al.* 2005) but this approach would be limited by the availability of suitable sequences.

#### 4. *How accurate is the TRM mechanism at capturing the contemporary geomagnetic field?*

It would appear that TRM can provide an accurate indication of the contemporary geomagnetic field. However, there are some caveats, which mainly relate to the collection, measurement and analysis of fired material. The standard guidelines for the processing and reporting of archaeomagnetic data cover these issues (Linford 2006), and should be adhered to in all practical work. In general, the implication is that magnetic minerals can consistently capture the ambient geomagnetic field on cooling through their Curie temperature outside tightly controlled laboratory conditions. Even with a low sample number, the success rate reported here is consistent with the results from Old Scatness, where a comprehensive archaeomagnetic sampling program had a 54% success rate. However, the results from this chapter indicate that the associated intensity of the archived signal and the mineralogy of the sediment have a significant impact on the accuracy of the recording mechanism. This has been recognised elsewhere (Chauvin *et al.* 2000; Catanzariti *et al.* 2008a; De Marco *et al.* 2008; Schnepf *et al.* 2009) and future attempts at developing a SVC should move towards utilising full vector (magnetic direction and intensity) data sets.

#### **6.7.1 Concluding remarks**

In this chapter, it has been observed that magnetic data from lake sequences are substantially smoothed compared to the discrete signals recorded by archaeological material recorded by either TRM or DRM. Whilst it is accepted that the British master curve does appear to provide a reasonable characterisation of geomagnetic SV, it cannot currently be combined with TRM data in any meaningful way to create a regional SVC. The main limitation is seen as the lack of realistic age-depth modelling to date the lake core sequences. Although these results are consistent with those from other researchers (Gallet *et al.* 2002), it was important to illustrate that all potential sources of data had been considered for inclusion in the updated British SVC. A final point worth emphasising is that the British archaeomagnetic database now contains DRM (or PDRM) directions. Fourteen of



the magnetic directions examined in chapter 4 were actually ditch fills, for example Keay's Lane (McCarthy 2000) or Yarnton (Linford *et al.* 2005), and in total there are 37 magnetic directions that originate from the DRM recording process in the British database (chapter 7). The results from Bigbury Camp and Hascombe described in section 6.5.2, illustrated that the two mechanisms for capturing the ambient geomagnetic were not significantly different within the limitations of the precision of dating available. As each pair of TRM and DRM directions from these sites were not significantly different from each other, it was considered reasonable that they should be allocated the same date range. If the 37 DRM directions were to be included, then it must be decided whether or not to include the lake sediment data, as they were recorded by the same mechanism. It is concluded that the issue lies with the lake data and not the recording mechanism. Although, it is unclear whether the problem with the lake data are due to issues with dating or obscuring of the signal through the sampling procedure, but probably both. Therefore individual DRM directions will remain in the British dataset and will be used to create future SVCs but the British lake data will continue to be excluded.

It is proposed that, in theory, it should be possible to combine magnetic directions from water-lain and heated sediments. The continuous record of palaeosecular variation recorded by British lake sediments and the British archaeological dataset are different, but not considerably so. These two archives do not match at discrete points in time but this is probably due to issues with dating the lake cores, that they were not aligned properly and related complications due to reliability of estimates of the sedimentation rate. This is taken to imply that with lake sediments there is no significant "lock-in depth". The application of the British lake master curve to archaeomagnetic studies is currently restricted by the lack of realistic age-depth modelling to date the core sequence from lake sediments. Although the same general trends first highlighted by the work of Turner and Thompson (1981) have now been observed in lake sediments across Europe, this chapter has provided evidence to suggest that the British lake master curve needs to be re-dated before it can be incorporated into any regional archaeomagnetic SVC

and used to “fill in the gaps” left by the nature of the archaeological record during the earliest period of the first millennium BC.

## **6.7.2 The future for British lake sediment data**

### *6.7.2i Reconstructing the British lake master curve*

Given the results from this chapter, it has been concluded that the current British master curve should not be included in the construction of a SVC. It would appear that the underlying assumption that the sedimentation rate was constant has created some problems with the application of dating evidence to the lake sequences. This situation has been compounded by using magnetic features as “tie points”, which has yielded a master curve with no real representation of the actual errors. There is an objective method of correlating two successions of data, i.e. sequence slotting (Thompson & Clark 1989). The necessary algorithms have recently been made easily accessible via freely available software CPLSlot (Mark Hounslow, Lancaster University). This program enables the user to compile data recorded from multiple successions to construct a composite record or stack of an environmental signatures preserved in the successions. It can then be used to determine an objective correlation between two or more sets of data to a base or reference section. Other research groups have developed their own algorithms to quantify the offset between results from several cores (for example Stanton *et al.* 2010: 612). It would be preferable if this work was done on the original data from the individual cores from British lakes before any statistical comparisons to magnetic directions from fired materials were undertaken.

### *6.7.2ii Resampling*

The main limitation to including the British lake master curve as part of the dataset used to create a regional SVC is seen as the lack of realistic age-depth modelling to date the core sequence. A potential method by which the high resolution record of palaeosecular variation recorded in lacustrine sediments can be fully exploited is by the use of isochrons to secure the sequence chronologically.

The current British lacustrine dataset of magnetic directions does not contain any isochrons that relate to the first millennium BC. It is possible that other sequences may contain suitable features, such as tephra horizons. Four tephra horizons have been identified in British sediments that fall within the first millennium BC GB4-150, Microlite, BMR-190 (Swindles *et al.* 2007) and Glen Garry (Barber *et al.* 2008) and thus are capable of providing a useful *terminus post quem* for sediment sequences relating to the British Iron Age. The problem would be identifying the presence of these tephra layers within the sample matrix recovered from British lakes. Lead isotopes could also provide useful isochrons as it was an important pre-industrial metal and there are distinctive peaks and troughs in the atmospheric pollution fallout from the Greco-Roman period onwards. The fallout can be considered instantaneous over larger geographical areas and lead is essentially non-mobile in lake sediments making trends in the lead isotope ratio potentially useful (Renberg *et al.* 2001). It is likely that in order to be implemented these approaches would require the collection of new lake cores, but this is a particularly worthwhile endeavour as it would enable the implementation of a new radiocarbon sampling strategy. One of the more pertinent developments in radiocarbon dating since the initial research by Turner and Thompson is the considerable reduction in sample size for radiocarbon determination. Within a carefully constructed and targeted sampling regime, this should enable higher resolution dating of lake sediment data from Britain. All of these suggestions were implemented with some success in a recent project in Sweden (Stanton *et al.* 2010).

#### 6.7.2iii Pattern matching and time-series analysis

Finally, visual comparison suggests that the British master curve is recording the same secular variation as another European dataset but this alone is insufficient to determine if the dates from one sequence could be transferred to another, or if two master curves could be combined. This combination is suggested as a method of taking the confidence in the age-depth modelling provided by the varved sediments in FENNOSTACK and applying it to the British un-varved lake sediments. A method that may fully quantify the problem is to perform some signal

processing techniques on the datasets to determine whether or not they showed the same general trends over time by treating the dataset as a continuous series rather than focusing on discrete tie points. There are two procedures common to signal processing that may be applicable: cross correlation and convolution. Cross correlation could determine how similar these two records of secular variation were and then a mathematical process called convolution would be able to identify the size of any differences between the two signals. It is possible to perform both of these procedures using Matlab®, a widely used program for doing mathematical computations. It would probably be necessary to first perform some data manipulation, so that all the datasets were sampled at the same interval rate and were of similar lengths and “unrolling” of the data.

Although some researchers have already produced the necessary programming code to perform some signal processing procedures on directional data (for example Jones 2006), this avenue of investigation would require more time than was feasible to allocate in this research, as it was necessary to prioritise other aspects, although other works have recently demonstrated that the application of Matlab to archaeomagnetism is valid (Pavón-Carrasco *et al.* 2011). Furthermore, this may only work if any differences were small and fairly constant down the sequence, and there is currently little evidence to support that assumption. It is also possible that there is insufficient data for this type of time series analysis to be robust. Therefore this remains a potential avenue for future work but future researchers are advised to keep in mind Anscombe’s quartet, although figure 6.7 suggests this may be successful.

## 7. The revised archaeomagnetic database for Britain with a discussion on secular variation curves

“The modifications that are often made from successive studies by different researchers prove that these curves are in constant evolution.” (Lanos *et al.* 1999: 376)

“It has long been an axiom of mine that the little things are infinitely the most important.”  
Sir Arthur Conan Doyle “A Case of Identity” 1892

### 7.1 Introduction

This chapter will describe how the revisions made to the prehistoric section of the British dataset will benefit any future secular variation curves (SVC) and how this will be an improvement on previous British SVCs. It will begin with a summary description of the complete British archaeomagnetic dataset that is now available as a result of this study, followed by a brief account on the different methodologies that have been employed to construct previous SVCs worldwide. This will be followed by a more in depth explanation on the Bayesian approach to SVC construction via RenCurve, which is how most current European SVCs are constructed. Then the overall effect of the re-evaluation of original data and the inclusion of new datasets will be explored qualitatively by two different approaches. The first is to compare the revised British dataset to the previous one (Zananiri *et al.* 2007). If the approach described in chapter 4 has been truly successful the new dataset should provide a similar but more precise description of past geomagnetic secular variation. The overall results from chapter 4 are presented in figure 7.1, to show that the dataset now has smaller age error estimates and that the temporal distribution of data is much improved, i.e. fewer data points are clustered around 350BC. The most obvious effect of the latter is the appearance of data points in the first millennium AD; this is the result of acknowledging the long chronology applicable to Scottish Iron Age sites. Furthermore the “strings” of data points concentrated around 350BC and AD1 in the original dataset have now vanished, which resulted from considering where each heated feature belonged in the overall site chronology and acknowledging that archaeomagnetism represents the end of use of a heated feature. These subtle, but previously overlooked, aspects have had

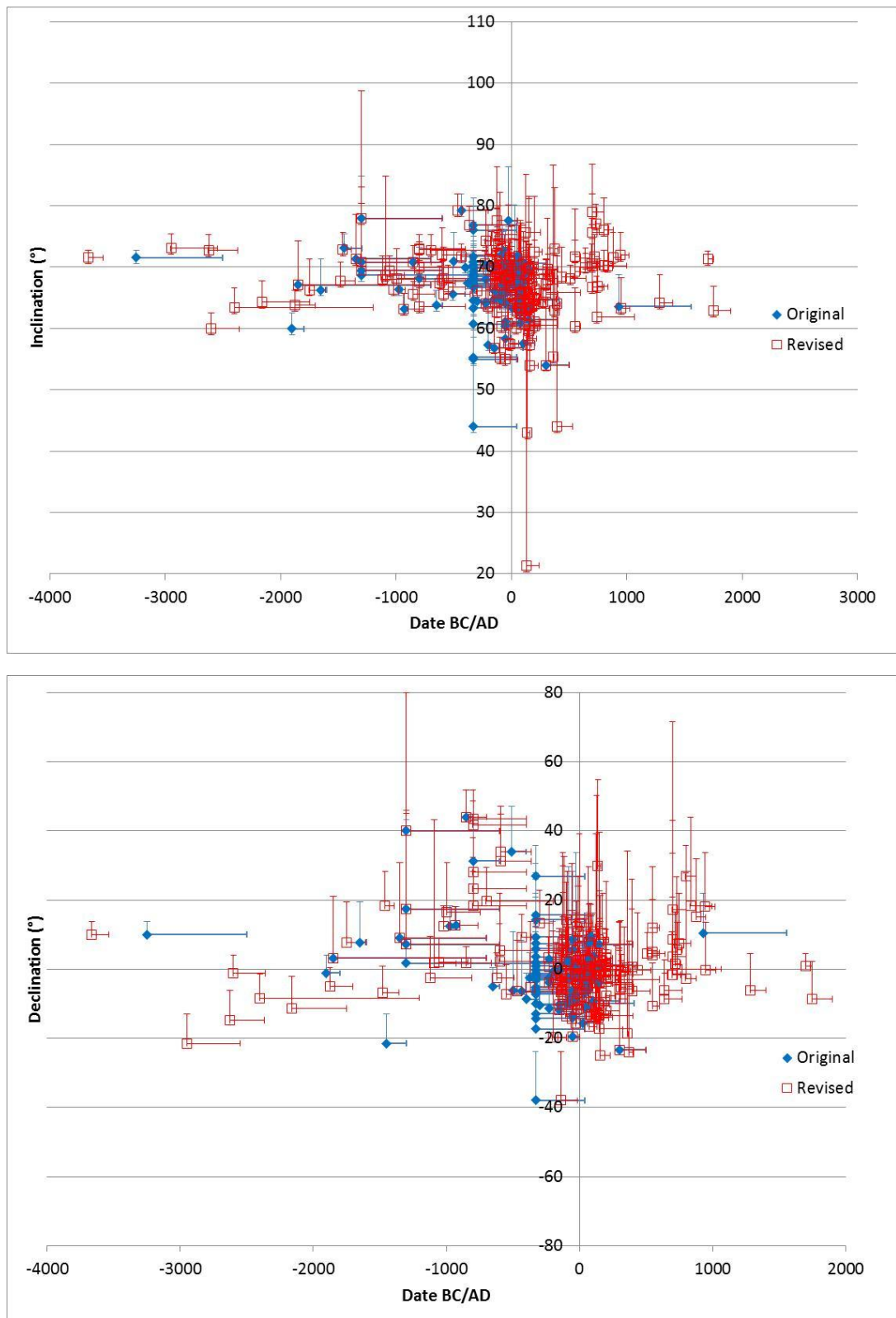


Figure 7.1: Graphs showing the difference made to the data examined during this research. Top graph shows inclination versus time and bottom graph is declination versus time, for clarity only positive errors are shown. This period now contains more data with a much improved temporal distribution. Note the data points in the first millennium AD are the result of acknowledging the long chronology applicable to Scottish Iron Age sites.

a significant impact on the spread of the existing data over time. The second approach is to compare the revised British SVC to other European datasets to investigate the behaviour of the geomagnetic field over a larger geographical region and to determine if this re-evaluation matches any global trends that have been identified and what this reveals about secular variation of the geomagnetic field. For reasons discussed in section 7.5 only a preliminary version of the revised SVC will be presented.

## **7.2 The British archaeomagnetic database**

The original dataset, as published by Zananiri and co-workers (2007), contained 620 archaeomagnetic directional data. This PhD research project has created a significant increase in the British database, as it now contains 919 archaeomagnetic directions. This is because all measurements from other laboratories were collated during the data collection process regardless of the type of site, but only those from Iron Age sites were re-evaluated in detail (as presented in chapter 4 and appendix 2). All these data have been included in the recently revamped British archaeomagnetic database, which is the result of a project that was conceived after this research but ran parallel to it. This project was called “Magnetic Moments in the Past: developing archaeomagnetic dating for application in UK archaeology” and was a joint venture between English Heritage and the University of Bradford with funding from the Arts and Humanities Research Council (AHRC reference AH/G01020X/1). The “Magnetic Moments in the Past” project was essentially a knowledge transfer exercise to raise awareness of archaeomagnetism within the archaeological community. The aim was to facilitate communication between commercial archaeologists, those working in the heritage sector and archaeomagnetic laboratories across the country. There were two main outputs from this project, one was the project web site ([www.brad.ac.uk/archaeomagnetism/](http://www.brad.ac.uk/archaeomagnetism/)), where details about the method were made available and the other was the development of an online database that will be available through the project website. The argument presented for completely overhauling and superseding Tarling’s online database (Tarling 1991) was to include

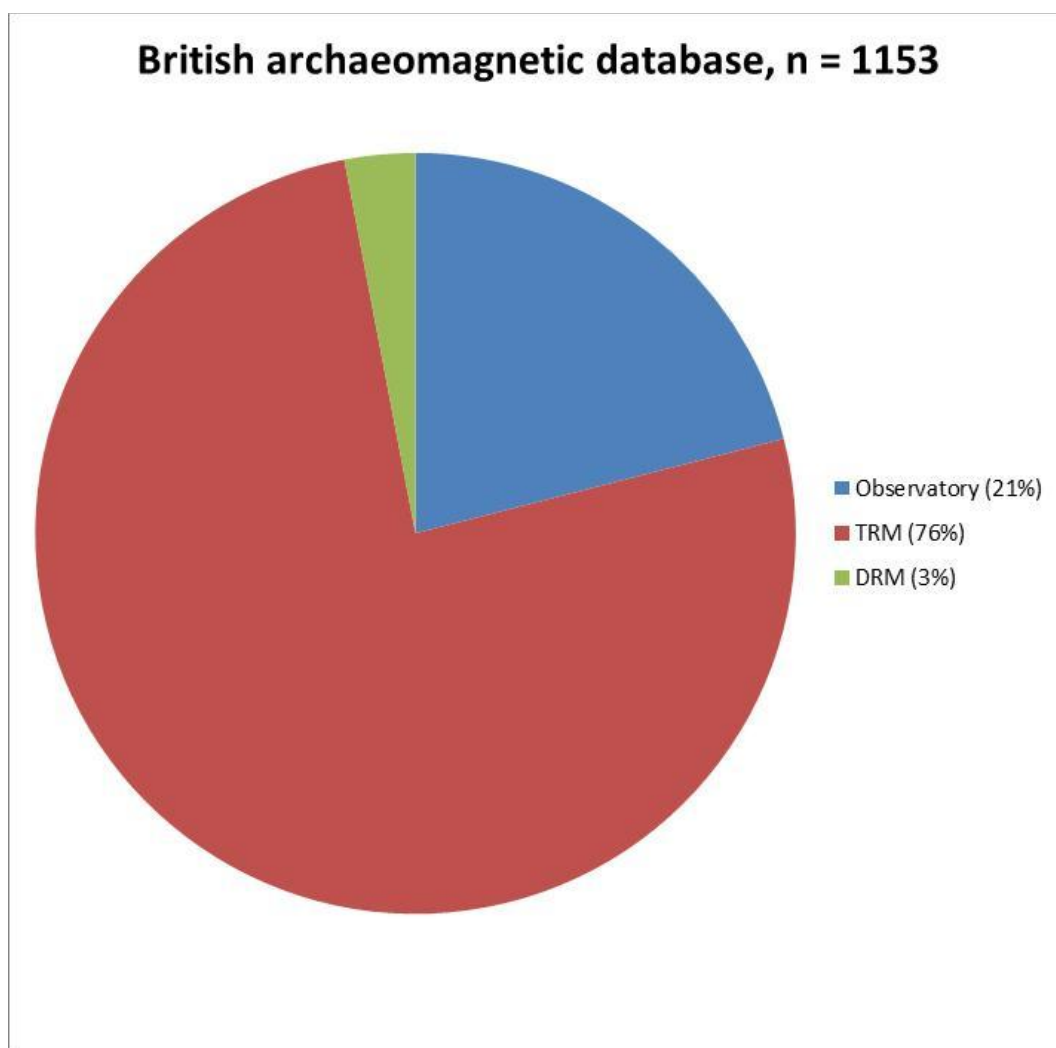
details that were of particular interest to archaeologists, for example the ability to search by archaeological feature type or by archaeological period. This revised database was created and developed by Dr Zoe Outram as part of the “Magnetic Moments in the Past” project but unfortunately, like its predecessor, this new database also utilised Microsoft Access so will probably require that the entire database is download before it can be queried, making it necessary to keep users informed of updates. Oxford Radiocarbon Acceleration Unit encountered a similar problem, which they have now avoided with OxCal 4 by moving to a completely online interface requiring users to log in and even allows them to save results to their server and download images suitable for publications. This approach would help with monitoring use and demand of the output of the “Magnetic Moments in the Past” project. The use of Access will also mean that the database will have little flexibility if it gets much larger.

Due to the combined efforts of “Magnetic Moments in the Past” and this research, the British database now contains 1153 data points. Of these only 1075 will be utilised to construct the revised British SVC (table 7.1). However, when considering the entire database, 79% are archaeomagnetic (directional) data with associated age estimates and 21% are direct observations of the geomagnetic field (Malin & Bullard 1981) (figure 7.2). Of the 919 archaeomagnetic directions in the database the majority (96%) were captured via thermoremanent magnetisation (TRM), with only 4% via depositional remanent magnetisation (DRM), (table 3.1 for details on the different recording mechanisms). The database now contains 37 examples of (P)DRM with four Bronze Age sites (Thanet (N=3), Farnley; Hartlepool and Caldicot (N=2)), seven Iron Age sites (Bigbury Camp; Felday Hillfort; Holmbury Camp; Little Bay; Moor Hall Farm; Mucking and Yarnton), four Roman sites (Keay’s Lane; Lincoln; ABC cinema (N=3) and Stakis Hotel), three early Medieval sites (Scots Dyke (N=2) Walton le Dale; Wharram Percy (N=9) and West Heslerton) two Medieval (Castle Acre (N=2) and Kingston) and two post Medieval: (Millmead and Wood Hall). Of the 919 magnetic directions from archaeological sites now in the British database, 255 have been examined in this research (28%). All of the output



Description	Number of data points	Comments
Total in British archaeomagnetic database	1153	All available data
Data from other laboratories without age estimates	46	Not used in this SVC
Data from samples collected for this research without age estimates	21	Not used in this SVC
Vitrified hillforts	8	Not used in this SVC

*Table 7.1: All data in the revised database and those data utilised to construct the revised British archaeomagnetic SVC.*



*Figure 7.2: Pie chart showing the composition of data types in the revised and updated British archaeomagnetic database.*

generated from this thesis, are available through this database. Copies of the data will also eventually be archived with the Archaeological Data Service (ADS, <http://ads.ahds.ac.uk/>) and the Magnetism Information Consortium (MagIC, <http://earthref.org/MAGIC>).

### **7.3 Developments in the method of estimating past geomagnetic secular variation**

Since the potential application of archaeomagnetic studies was recognised (Thellier 1938), several different approaches to representing past secular variation in the Earth's magnetic field (EMF) have been proposed (Aitken 1958; Clark *et al.* 1988; Sternberg & McGuire 1990b; Wolfman 1990b; Batt 1997; Le Goff *et al.* 2002; Lanos 2004) but all approaches have to deal with four main problems before attempting to estimate past geomagnetic secular variation:

1. The available archaeomagnetic data are unevenly distributed in time and space;
2. The dating evidence, or how the age estimates for each of the magnetic directions are obtained is problematic;
3. The geomagnetic field has three components and determination of past field direction is not always accompanied by intensity (or never in the UK);
4. The available archaeomagnetic results have been obtained via different sampling methods and measurement procedures leading to different precisions on the measurements.

This research has focused on improving the situation for the first two problems and the following account will describe each of these problems in detail and describe how previous researchers have dealt with them.

#### **7.3.1 Problem 1: Uneven distribution of data**

The nature of archaeological evidence means that some locations and periods of time yield more magnetic data than others. Furthermore, the acquisition

of more data is dependent on the discovery of suitable and well-preserved archaeological remains. All previous researchers have stated the need for additional data and recognised that reconstructing past secular variation of the geomagnetic field is an on-going process. Nevertheless, it would be preferable to find a method to compensate for the irregular dispersal of data and it was hoped that the continuous records of secular variation in the geomagnetic field archived in lake sediments may have been able to address this issue, (chapter 6). As this approach would require a new programme of sampling, it was beyond the scope of this project, so this only leaves the available archaeomagnetic data with the associated uneven temporal distribution (figure 4.15). It had been presumed that as long as there were at least five data points per century, this would be sufficient to describe the past secular variation (Aitken 1990: 243). The underlying assumption to this claim was that there was some underlying periodicity to the geomagnetic field, which is now believed to not be the case, so this estimate has been revised to 10 data points per century (Bucur 1994). In the course of this research the collation of data (chapter 4) and programme of fieldwork (chapter 5) has been unable to obtain 10 data points for many, particularly prehistoric, centuries. Neither has it proven possible to identify a periodic pattern to the geomagnetic field, so the uneven temporal distribution of data remains a problem that needs to be addressed.

Another problem is the uneven spatial distribution of data; which could also be addressed by incorporating more data (chapters 4, 5 and 6) but it has been found that this could be compensated for if magnetic data underwent some form of relocation procedure (Shuey *et al.* 1970). This involves reducing the data to a central location to compensate for spatial differences in the geomagnetic field across the Earth's surface. Whereas the distribution of inclination does closely match that of a uniformly magnetised sphere, only 80% of the observed geomagnetic field can be described in terms of a single geocentric dipole. The remaining 20% of the observed field is referred to as the non-dipole field and imposes a restriction on the area over which data can be relocated, which is currently set as an area of 500km radius from the reduction location. Two different

methods of reducing data to a central location have been proposed, the geocentric axial dipole hypothesis (GAD) or using a virtual geomagnetic pole (VGP) as an intermediary. The GAD hypothesis assumes that the measured value of declination is not modified by the position on the Earth's surface so only the inclination is corrected according to a geocentric axial dipole field for differences in latitude (for example Aitken 1958; Burlatskaya *et al.* 1969; Thellier 1981). The VGP method (Irving 1964) uses an inclined geocentric dipole hypothesis to calculate the geographical coordinates of the VGP from the site values of declination and inclination and then to the corresponding direction for the central location. Subsequent research has demonstrated that the VGP method is more efficient and provides better grouping (Shuey *et al.* 1970; Bucur 1994) and it forms the basis of the method employed in this study (Noel & Batt 1990), (section 5.2.6).

### **7.3.2 Problem 2: Inadequate dating evidence**

By the 1970's a substantial body of archaeomagnetic data had been collected, which were suggesting that the geomagnetic field did not alter in a predictable manner (Tarling 1983: 171ff). This discovery had important implications for future attempts at SVC construction, so an attempt was made to verify the theory behind the hydromagnetic dynamo origin of the EMF (Burlatskaya & Braginsky 1978). Unfortunately, the errors on the archaeomagnetic data were large enough to encompass both models of the EMF, making it difficult to distinguish between them. Eventually, it was becoming apparent that it was the dating errors that were limiting any attempts to estimate past secular variation regardless of the type of archive utilised: archaeological, marine or observatory records (Cong & Wei 1989). This problem with dating evidence has been acknowledged by all workers since the 1980's (for example, Barton 1982; Bucur 1994; Márton 2003; Donadini *et al.* 2009) but has never been fully dealt with. It requires a clearer understanding of the nature of archaeological evidence, how it is applied, its strengths, limitations and how to account for these in any statistical model of secular variation. Furthermore, it is now being recognised more widely that a preliminary date range based on archaeological evidence can change after detailed post-excavation

analysis (Kovacheva *et al.* 2009). Indeed, focusing on this detail has formed a major preoccupation of this research (sections 4.4 and 4.5).

### 7.3.3 Problem 3: Incomplete data

The geomagnetic field is a vector quantity, so has a direction and strength, (figure 3.2). Therefore as the purpose of most archaeomagnetic studies is to develop models of past changes in the geomagnetic field, these models should be based on a complete description of the field (Rolph *et al.* 1987; Lanos *et al.* 1999). Current published databases tend to focus on one aspect of the magnetic field, either direction, for example Britain (Zananiri *et al.* 2007 and this research), Spain (Gómez-Paccard *et al.* 2006), Italy (Tema *et al.* 2006), Hungary (Márton & Ferencz 2006; Márton 2010), USA (Sternberg & McGuire 1990a; Lengyel & Eighmy 2002; Hagstrum & Blinman 2010), Mesoamerica (Goguitchaichvili *et al.* 2004; Hueda-Tanabe *et al.* 2004), North Africa (Tarling *et al.* 2003; Rimi *et al.* 2004) and Korea (Yu *et al.* 2010) or intensity for example Greece (De Marco *et al.* 2008), western Europe (Gómez-Paccard *et al.* 2008) and India (Ramaswamy & Duraiswamy 1990). However, there are some examples of databases containing full vector data including France (Gallet *et al.* 2009), central Europe (Schnepp *et al.* in prep), Bulgaria (Kovacheva *et al.* 2009) and some studies on lava flows (Rolph *et al.* 1987; Tanguy *et al.* 2003, Tanguy *et al.* 2011). There appears to be a growing trend in archaeomagnetic research to move towards using full vector data as there is mounting evidence to suggest that the associated intensity of the archived signal is an important factor contributing to the accuracy of the recorded magnetic direction (Chauvin *et al.* 2000; Catanzariti *et al.* 2008a; De Marco *et al.* 2008; Schnepp *et al.* 2009; Pavón-Carrasco *et al.* 2011; section 6.6). This still leaves the problem of how to cope with the available data, particularly how to incorporate measurements of displaced material such as bricks that will only provide at best details on inclination, for example the data from briquetage fragments from East Anglia, UK (Borradaile *et al.* 1999). Here the development of a method of curve construction, RenCurve (Lanos 2004), may prove invaluable and is discussed further in section 7.4.

#### **7.3.4 Problem 4: Different precision of collated datasets**

The British archaeomagnetic database contains a selection of different types of data (table 7.1), including observatory data and archaeomagnetic data, recorded by both thermo and depositional remanent magnetisation. An important quality of archaeomagnetic data is that the archived direction is only representative of the actual ambient geomagnetic field (figure 3.3 and section 3.4). In addition, the collated data is representative of over 60 years of research from several different laboratories and some methods of retrieving archaeomagnetic data are more reliable than others. This has led to the British archaeomagnetic dataset becoming an array of different data types with differing quality. This subtle problem has been largely overlooked as previously there was no way to quantify, never mind compensate for any differences. Only in recent years has a viable method of dealing with this problem been developed. The solution was both elegant and sophisticated; it involved creating a Bayesian hierarchical model of the experimental errors (Lanos 2005). This approach reflects the nature of archaeomagnetic data as it is able to represent the heterogeneity of the magnetisation within the material sampled, whilst also allowing the presence of any systematic errors due to sampling or measurement protocols to be identified. Essentially, it recognises that the process of obtaining archaeomagnetic data is a descending hierarchy and recreates it mathematically so all the accumulative errors at each stage of the process can be described and their probability distributions established. This is a more erudite and functional approach that enables the percentage errors quoted in figures 5.3 and 5.4 to form part of the method of SVC estimation and is called RenCurve (Lanos 2004).

#### **7.3.5 Methods of representing past geomagnetic secular variation**

Even after obtaining an estimate of the nature of change in the geomagnetic field, the next problem is how to estimate the secular variation of the geomagnetic field and provide a visual representation of it. The first attempts to describe the past secular variation experienced by the EMF were presented as separate plots of

declination or inclination against time (for example Cook & Belsché 1958; Aitken 1970; Burlatskaya *et al.* 1970; Thellier 1981), whereas other workers chose to use Bauer plots (Clark *et al.* 1988; Sternberg & McGuire 1990b), plotting inclination against declination and time was marked along the curve (figure 2.2). Until relatively recently SVCs were hand-drawn (examples include Clark *et al.* 1988; Wolfman 1990a; Hueda-Tanabe *et al.* 2004), however, this method cannot fully take into account all the errors associated with each data point described in section 7.3 and the resulting pattern of change is highly subjective. Several different statistical solutions to this problem have been suggested (Clark & Thompson 1978; Thompson & Clark 1981; Clark 1983; Le Goff *et al.* 1992; Batt 1997; Le Goff *et al.* 2002). Of these the moving average method became the most popular and different approaches to smoothing schemes were suggested (for example, Sternberg & McGuire 1990b; Daly & Goff 1996; Márton 1996; Batt 1997), with each group having a preferred “window” width and weighting criteria. In many respects these discussions were largely redundant as the moving average technique is fundamentally unsuitable for the situation presented by archaeomagnetic data. The moving average technique was developed for use with time-series data to smooth out short-term fluctuations of numerous, precise data that are evenly distributed over time. As highlighted in section 7.3.1, archaeomagnetic data are not evenly distributed over time, although the use of “weighted windows” did start to compensate for this inherent deficiency in the dataset.

Further developments in the moving-average method, enabled the treatment of the data to reflect the spherical nature of magnetic data and to treat it as bivariate (Le Goff *et al.* 1992). Others workers still treated the data as univariate (Márton 1996) but the question of the size of “window width” remained (Márton 2003) and the choice appeared to be arbitrary. It was not until the incorporation of a Bayesian approach to the construction process that it was possible to develop a method, RenCurve, which takes into account all of the errors associated with the magnetic data in the curve estimation process simultaneously and which automatically adjusts to the variability of the dataset (Lanos 2004). By employing

RenCurve, it is possible to obtain a functional envelop on the secular variation curve. In other words, this software addresses the issues raised by Batt (1997; 1998); particularly regarding extensive interpolation in certain periods, and the lack of assessment or representation of uncertainties in the SVC to provide an estimate of error associated with the curve that actually reflects the variability of the dataset used to generate it. Therefore at the time of this research RenCurve was the logical choice for the construction of an updated British archaeomagnetic SVC.

#### **7.4 The RenCurve method of SVC estimation**

There are three main reasons for selecting the specialist software RenCurve (Lanos *et al.* 1999; Lanos 2004; Lanos *et al.* 2005) to produce an estimate of past geomagnetic secular variation over Britain:

- it provides a comprehensive and robust method for handling many of the inadequacies in archaeomagnetic data (Lanos *et al.* 2005)
- it has quickly become established as the standard method of producing SVC across Europe with the regional curves for France and Bulgaria (Lanos *et al.* 1999; Lanos *et al.* 2005), Germany (Schnepp & Lanos 2005), Austria (Schnepp & Lanos 2006), Hungary (Márton & Ferencz 2006), Italy (Tema *et al.* 2006), Iberia (Gomez-Paccard *et al.* 2006), and Romania (Suteu *et al.* 2008) all utilising this software.
- the previous SVC for Britain (Zananiri *et al.* 2007) used an earlier version of this software, therefore using the same software would make comparisons more straightforward and the implication is that any differences between the two curves would primarily be due to the improvements and additions made to the dataset.

This section provides a description of how RenCurve produces an estimate of past geomagnetic secular variation from archaeomagnetic data. The data in the British archaeomagnetic database represents 60 years of research and is the collective output from six different laboratories, which all utilised different sampling



procedures, measurement protocols and methods of data processing. Also, all the archaeomagnetic directions are presented as at site, but to be used to estimate past secular variation they require reduction to a single location as the geomagnetic field displays spatial as well as temporal variation, for historical reasons in Britain the chosen location is Meriden ( $\gamma = 52.43^\circ$   $\lambda = -1.62^\circ$ ). It has been found that when relocating magnetic directions using the Virtual Geographic Pole (VGP) method (Noel & Batt 1990) the difference in angular distances is typically  $<1^\circ$  and up to  $2^\circ$  if relocating from London, UK to Tunis, Tunisia (Gallet *et al.* 2002). This is a distance of 1826km (1135 miles) and a change in latitude of over  $15^\circ$  south. Other research has suggested that changes in longitude makes the biggest difference with larger errors appear to be incurred if the relocation involves more than  $6^\circ$  east or west (Schnepf & Lanos 2006), whereas others suggest that for European sites, errors of  $0.25^\circ$  per 100km of relocation can be expected (Casas & Incoronato 2007). The British Isles covers an area on the surface of the Earth of  $12^\circ$  of latitude and  $10^\circ$  of longitude, as the current reduction location is Meriden this means that the largest longitude correction will be  $5.8^\circ$  from South Uist (Western Isles), which is just with the limits stated above. For completeness the largest correction of latitude applied is  $8.3^\circ$  from Unst (Shetland Isles), therefore it is postulated that the errors introduced by reducing data from across the British Isles should not exceed  $1^\circ$ .

#### **7.4.1 Bayesian hierarchical model**

The process of producing an estimate of secular variation using the RenCurve algorithm breaks down into four main stages, each of which attempt to address the main issues encountered when attempting to estimate past secular variation (section 7.3). The first stage focuses on the third problem highlighted by Lanos, (2004) namely that the results available were obtained via different sampling methods and measurement procedures led to different precisions on the available measurements. RenCurve overcomes this problem by utilising a Bayesian hierarchical approach (Lanos *et al.* 2005) to model the potential experimental errors. Essentially it permits the archaeomagnetic directions as published to be utilised, therefore it is not necessary to obtain the original measurements and

recalculate the mean direction at site for every data point. The hierarchical approach is particularly inspired as it reflects the nature of data acquisition in archaeomagnetic studies and effectively standardises the data, meaning it removes any differences due to different sampling or laboratory procedures. It is then these “standardised” data that are reduced to a single location, enabling the presence of any systematic errors to be identified (Lanos *et al.* 2005). The application of this approach has shown that if it can be demonstrated that all the errors are random, the inclusion of directions with large  $\alpha_{95}$  values will not increase the error envelop of the resultant curve. The implication of this is that the entire dataset should be used without any subjective filtering or prior selection of the “best” data. RenCurve can now also incorporate information on the weighting protocol developed by Chauvin and co-workers (2000), which does provides a qualitative assessment of the reliability of the range of different measurement protocols available, table 4.3. This has the effect of further refining the understanding of the precision on the data. It appears to have been general practice in Britain to only examine the direction component of the archived geomagnetic field (section 2.5) and typically demagnetisation is carried out by tumbling in an alternative field (section 5.2.4). In the UK database there are limited exceptions, for example in Aitken and Hawley’s (1967) work that used thermal demagnetisation, but without the original laboratory reports it is not possible to fully apply Chauvin’s (2000) criteria. Therefore all of the British data in the database (appendix 1), have been weighted 1 with the exceptions listed in table 7.2, which were weighted zero.

Site	Sample reference	Reason
Old Scatness	AM36, AM43, AM63, AM33	Archaeological evidence to suggest that the material sampled was re-deposited ash
Mine Howe	MH1/AM77	Material sampled was no longer in situ
Wharram Percy	PP/QQ/171, W176, “Ditch silts”, KK172	These data have unusually shallow inclinations and declinations nearing 180° so require further examination

*Table 7.2: Data from the British database that has been weighted zero with reasons for this decision.*

### 7.4.2 Prior information

The next stage is to produce an estimate of the secular variation over time as represented by the archaeomagnetic directions within the dataset. The geomagnetic field is a physical and continuous process (chapter 3), so even though its variation is unpredictable there is a connection between the geomagnetic elements over time. RenCurve allows for this connection by incorporating prior knowledge of the global nature of the geomagnetic field,  $g(\cdot)$ , the path on a unit sphere. Therefore what we currently understand about how the geomagnetic field is produced provides a Bayesian inference of the curve, meaning the estimate is constrained by established assumptions about the nature of the geomagnetic field and its path on the unit sphere. Previous researchers have suggested that the optimum choice for this function is a ‘penalized spline’, however this is mathematically complex to implement on archaeomagnetic data as the latter is spherical. Lanos (2004) avoided this issue by “unrolling” the data at this stage in the curve construction, a process well established in cartography for producing zenithal (or azimuthal) equidistant projections. This is just a method of taking a curved surface and displaying it as a flat surface, particularly useful for producing navigational maps (for example air routes) as it preserves radial distances, making it also ideal for converting archaeomagnetic directions with no loss of information. By implementing this data manipulation, the data follows a Gaussian distribution and the use of natural cubic splines to estimate the function of the geomagnetic field becomes straightforward. A further benefit of this approach is that the amount of

smoothing applied to the curve becomes responsive to the nature of the dataset and will only depend on the distances between the time knots. This more sophisticated approach is superior to previous curve estimation techniques that heuristically selected window sizes for the moving average approach, as it automatically adapts to the density of points along time (Lanos *et al.* 2005; Márton & Ferencz 2006), which provides an estimate of secular variation whose precision reflects the distribution of data utilised to produce it.

This ingenious approach to curve estimation can also take into account some qualitative information such as stratigraphic constraints provided by archaeology, something that Zananiri *et al.* (2007) did not exploit. In the revised SVC, full use will be made of all the available archaeological information. This has not only included revising the age estimates as described in chapter 4 but extended to including details on the form of the dating densities, (figure 4.2) and applying some relative stratigraphic constraints that incorporates prior knowledge on the relative order of features, as recovered from archaeological observations. In the 94 sites examined in detail it was possible to include additional stratigraphic information on the relationships between features at seven sites: Cladh Hallan (N=9), Old Scatness (N=33 out of 44), Hascombe hillfort (N=2), Bigbury Camp (N=2), Scots Dyke (N=2), Sherracombe Ford (N=2) and Wickham (N=2). At Cladh Hallan there were direct relationships between all the hearths whereas at Old Scatness it was only possible to include the stratigraphic relationships within some of the structures. The sites of Hascombe hillfort and Bigbury Camp both had archaeomagnetic directions recorded by TRM and DRM with statistically the same direction and had been given the same age range (appendix 2) but due to the nature of the archaeological deposits it was assumed that the TRM data must have been captured before the DRM. From an archaeological point of view the last use of any hearths should occur before a settlement is abandoned, but silting up of wells or ditches will only occur after the population have moved on. At Scots Dyke two samples were collected from the same ditch profile, and at Sherracombe Ford samples were collected from two different linings of the same furnace structure so with both of these the relative

order relations were straightforward. Finally at Wickham two hearths were sampled where the later feature cut into the earlier one, so again the relative order of events was simple. In the version of RenCurve utilised here it has been possible to further extend the second stage by applying weighting for the reliability of the associated dating evidence. The weight column W is usually used to qualify measurement process (Chauvin *et al.* 2000), but following the criteria outlined in table 4.4 it has been adapted for this purpose, where A=4, B=3, C=2 and D=1 and these weightings have been added onto those applied for the measurement process for this version of the British archaeomagnetic SVC. It is hoped that future versions of RenCurve could consider the issues of questionable dating as discussed in chapter 4 in a more considered and rigorous manner. The most likely approach would be to incorporate a method of down-weighting the prior dating densities (whether uniform, multimodal or Gaussian) that are considered on archaeological grounds to be unreliable.

### **7.4.3 Smoothing parameter estimation**

The third stage uses Markov chain Monte-Carlo method (MCMC) sampling to determine the optimum smoothing parameter between smoothing and fitting (Gilks *et al.* 1996). This is a widely used algorithm, which assures a rapid convergence to the desired and pre-determined level of precision. An additional benefit in the application of this algorithm in this instance is that it also allows posterior densities of the dates and global variance to be estimated simultaneously. This effectively reduces the overall computation time. A version of this algorithm is also employed in the OxCal software, which is widely used in archaeology. Users of OxCal will be familiar with the Agreement Index (Bronk Ramsey 2009) and RenCurve also calculates how well the posterior matches the data and from this the user can either continue the computations or make some adjustments, here the observatory data provides a very useful test on the model's performance. The ability to fix the time knots and degree of global variance can be useful if the distribution of data points over time is uneven and provides a posterior density of secular variation that is Gaussian. If random time knots and global variance are used the posterior density

of  $g$  may not be random but the configurations will be in agreement with any stratigraphic constraints that have been introduced. For currently published Bayesian SVCs generated using RenCurve (Schnepp & Lanos 2006; Gallet *et al.* 2002; Schnepp & Lanos 2005; Gomez-Paccard *et al.* 2006; Tema *et al.* 2006; Zananiri *et al.* 2007), these calculations were performed by MCMC sampling and generally it was necessary to run nearly 500 000 iterations until the precision of the Bayesian time estimates were within two years of each other. The best smoothing parameter,  $\alpha$ , is generally found via systematic exploration and is used to derive the corresponding Bayesian calibration curve with an error envelop.

#### **7.4.4 Posterior curve distribution**

The final stage is where the estimated curve is plotted using a natural cubic spline interpolation function and the advantage of this is that the 95% posterior density interval or the 95% “error envelop” that contains the true curve is calculated simultaneously. The calibration curve is finally obtained by “re-rolling” the parametric curve from the plane ( $xy$ ) back onto the sphere. This provides a spherical spline which has a functional envelop of error and is actually representative of how well we can estimate the past secular variation of the geomagnetic field. The hypothesis of descending hierarchy appears to provide an adequate model of the actual nature of archaeomagnetic data (assuming that any errors present are random) and removes any potential bias due to the collections, measurements process or number of samples used to produce the mean direction. The inclusion of prior information on the nature of the dating evidence, relative order of events and the physical properties of how the geomagnetic field behaves on the surface of sphere enables an estimate of the curve that is natural and realistic. In combination, this approach means that the precision of the geomagnetic SVC is essentially controlled by the number of data points and the errors in the archaeomagnetism are dominated by errors in age. Therefore the work carried out in this research project has focused on the two aspects that can do most to improve the British SVC (sections 4.2, 5.1 deal with collating more data and section 4.4 deals with reducing archaeological age error estimates). In the rest of this chapter a

preliminary version of the new curve will be compared to the most recent British SVCs (Clark *et al.* 1988; Zananiri *et al.* 2007), other European SVCs and lake master curves to determine if this is the case.

#### **7.4.5 General observations on the revised British archaeomagnetic dataset**

The estimated geomagnetic secular variation as derived from initial processing of the revised dataset ready for curve estimation via the RenCurve algorithm is shown in figure 7.3. This plot shows a first trial of curve estimation with the revised dataset and raw data used to produce it courtesy of Philippe Lanos. It represents the first two stages of the process described in sections 7.4.1 and 7.4.2, and the data treatment is spherical although in figure 7.3 it is presented as univariate. At this stage the errors with time have not been accounted for, just the errors and hierarchical treatment of the magnetic data. The raw data currently appear to be well represented but this may alter as at this stage no modelling has been undertaken, and there is no error envelope associated with the curve. Any points that fell outside the range 58°-76° for inclination or 338°-32° for declination had generally already been weighted zero before processing through RenCurve (table 7.2), because either the magnetic or temporal data had been considered to be unreliable, following the criteria presented in section 4.3.

In this preliminary curve, the first millennium BC shows some rapid fluctuations with two cycles peaking in inclination during this period. This overlies an overall trend of increasing inclination up to the middle of the fourth century BC then it starts a steady decrease and reaches its lowest point at around the middle of the third century AD. In figure 7.3, inclination shows four peaks between 3500BC and AD500 at around 365BC, 700BC, 1400BC and 2650BC. Declination currently shows five peaks between 3500BC to AD500, at around 2500BC, 1700BC, 1300BC, 800BC and 250BC. By far the most significant peak is at 800BC. The lowest declination point in the preliminary curve appears to occur during the middle of the second millennia BC but this section of the curve currently is based on very few

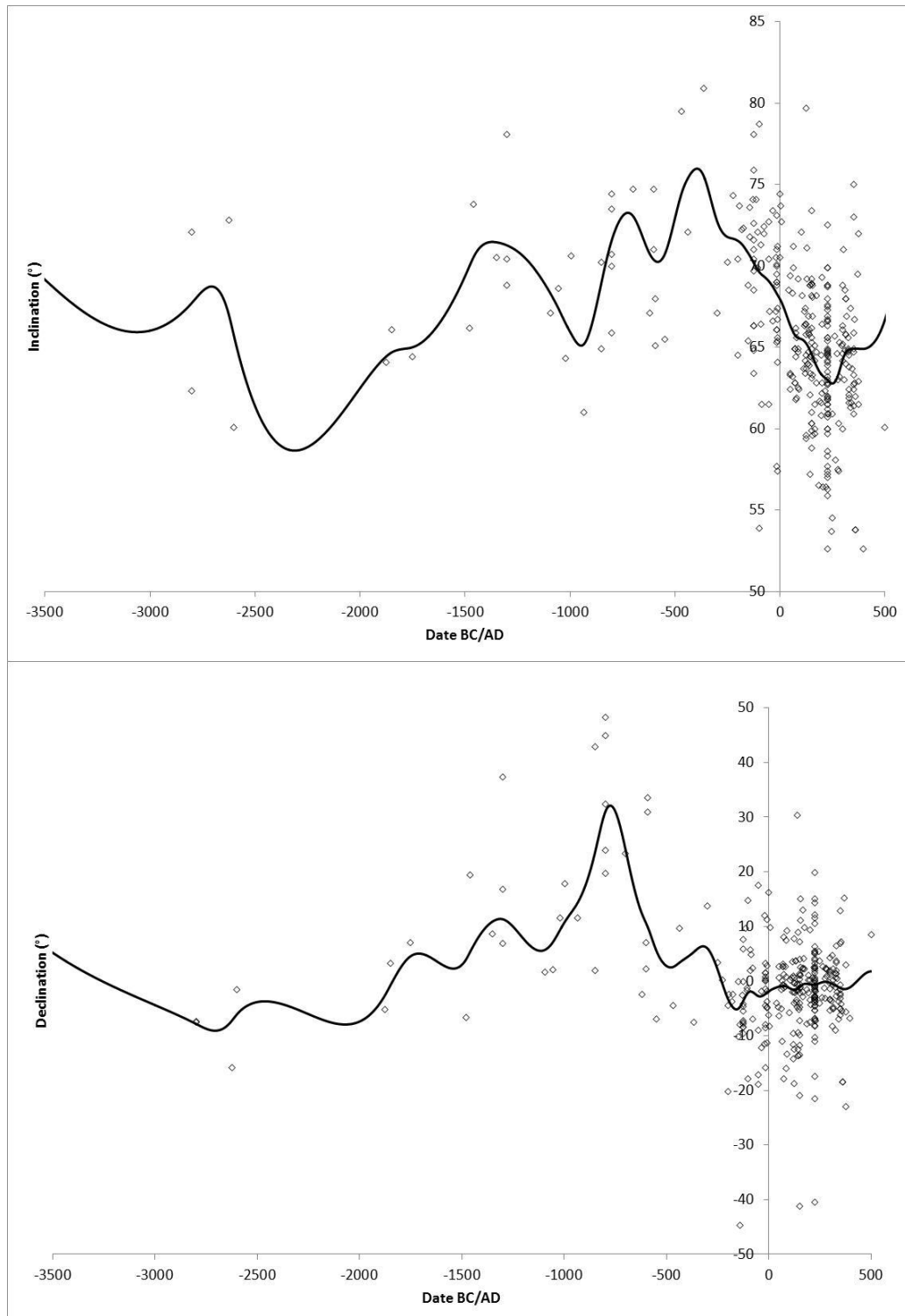


Figure 7.3: Graphs showing the preliminary estimate of geomagnetic secular variation as derived from the revised dataset which is also plotted, inclination versus time is shown at the top and declination versus time at the bottom. The revised SVC presented here represents the curve after stage two of the curve generation process so has not undergone the Bayesian approach to errors on time or MCMC sampling and so has no error envelop. Note these graphs focus on the target period, of the first millennium BC.



data, there is another low around the middle of the second century BC. So declination during the first millennium BC appears to be marked by a rapid increase occurring in less than two centuries, to the highest value recorded over the last 5000 years, followed a general decreasing trend with a small recovery around 300BC. It would appear that inclination also experienced more changes during the first millennium BC than was previously anticipated.

### **7.5 Comparison with previous British secular variation curves**

The preliminary version of the revised SVC for Britain presented in this section was produced by Philippe Lanos at l'Université de Rennes. The updated British dataset resulting from the combined efforts of "Magnetic Moments in the Past" and this research was used by Lanos to test a series of updates and improvements to the RenCurve algorithm. These updates are currently incomplete and will be published shortly (Lanos pers. comm. 2011); so will not be discussed here other than to state that they have focused on the errors with time and enable potential outliers to be quantified. It should also be able to demonstrate whether the associated age estimate is the likely source of the error, which may prove to be a particularly useful tool in the future. As with most software development, this process underwent a series of developmental issues, which delayed the completion of this research but some preliminary results were made available (figure 7.3) to enable some qualitative comparisons to be made. This discussion is based only on these preliminary results, so the findings presented here may change when the final curve is released. It will also focus on the first millennium BC as this was the target period for this research. The rest of this chapter will focus on the impact of the additions and amendments resulting from the work carried out during this research as suggested by these preliminary results.

The changes made to the associated age control on the archaeomagnetic data have had a significant impact on the first millennium BC section of the curve. When compared to the most recent British SVC, figure 7.4 the most immediate

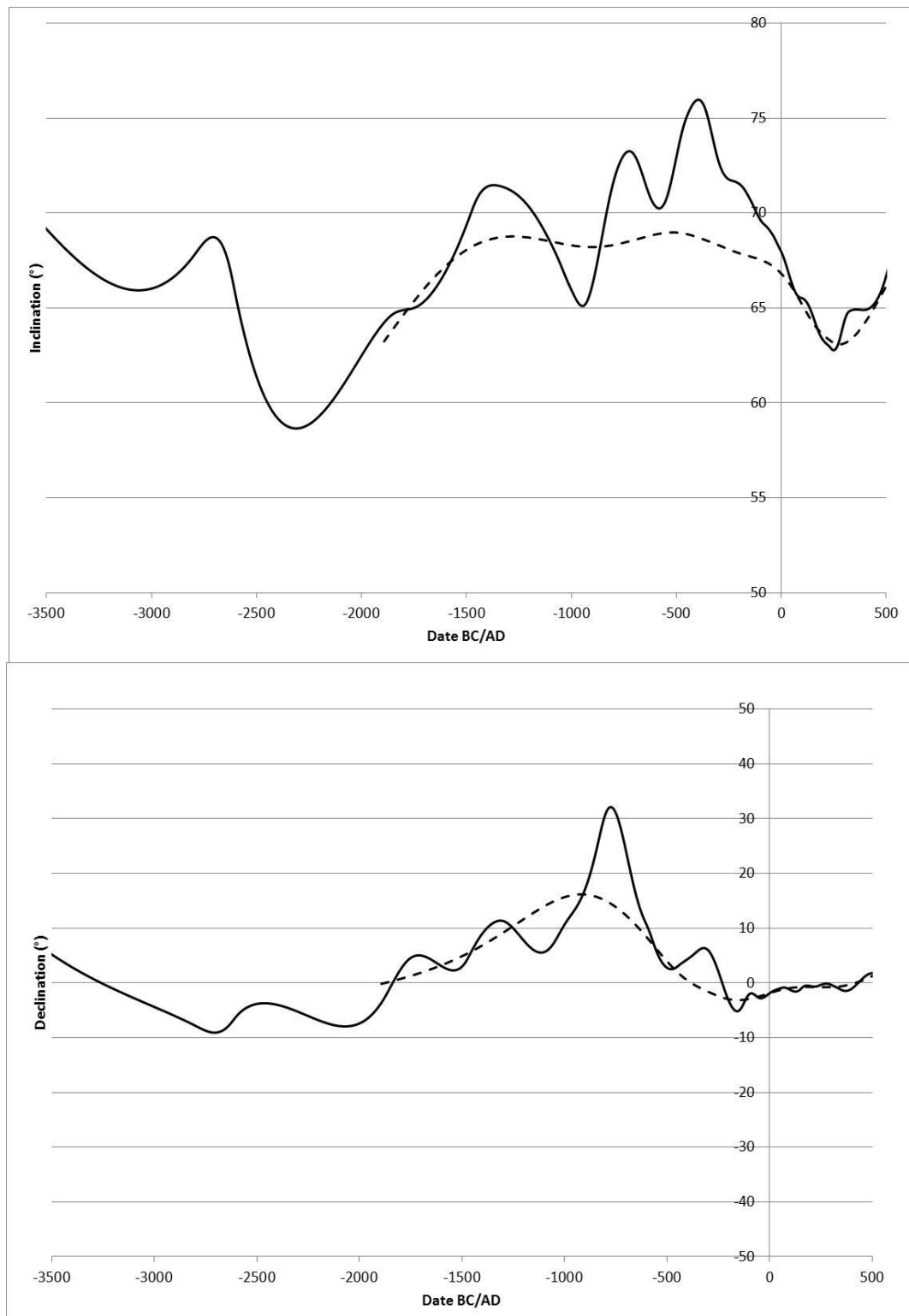


Figure 7.4: Graphs showing a comparison between the estimated geomagnetic secular variation before and after the re-evaluation process, inclination versus time is shown at the top and declination versus time at the bottom. The preliminary version of the revised SVC is shown as a solid line and the previous SVC (Zananiri et al. 2007, also see figure 7.6) is a dashed line.

improvement is that this section of the curve now displays much more structure than was previously apparent. The revisions made to the data show that both declination and inclination experience more frequent and higher amplitude changes in direction. Inclination shows the most marked change, with three clear peaks during the first millennium BC, which should prove to be particularly helpful for archaeomagnetic dating purposes. Furthermore, the large, rapid change in declination at the beginning of the first millennium BC, observed in lake sediment records across Europe (Turner & Thompson 1982; Stockhausen 1998; Ojala & Saarinen 2002; Snowball & Sandgren 2002; Frank *et al.* 2002a; Ojala & Tiljander 2003; Nourgaliev *et al.* 2005; Snowball *et al.* 2007) is now much more apparent in the preliminary results compared to the previous SVC. When it is considered that the revised dataset is composed entirely of magnetic directions from archaeological artefacts, this is taken to suggest that a rapid change in declination during the first millennium BC is a real phenomenon and not the result of any data processing.

This leads onto a comparison with the “Clark curve”, the first SVC to extend into prehistory; as this curve (Clark *et al.* 1988) based the first millennium BC section of the curve entirely on the published lake sediment data from British lakes (Turner & Thompson 1982). It would appear that there are some differences between the curve produced from lake data and that produced from archaeological data, figure 7.5. The main source of the difference appears to be the inclination values and the timing of the peak of the swing in declination values. There are other differences as well, the famous “Roman hair pin” is no longer present but it appears to have now been replaced by a middle Iron Age hair pin feature where 520BC and 265BC bisect with the peak at 390BC. Another feature of the Clark *et al.* (1988) curve was a rapid change in inclination previously seen during the late Roman period from AD200-500, whilst a change in inclination is still present during this time, it is not as pronounced. Finally, the collation of new data and the revision of existing data have enabled the SVC to be extended further back into prehistory. The British SVC now extends back to 3600BC although there are relatively few data describing this section of the curve, (figure 7.3). After 2000BC the curve is only

constrained by data from three sites, Easington (Mackay 2001), Ringlemere Farm (Linford 2008) and Moel y Gerddi (Kelly 1988). It is hoped that this new curve will provide an additional method of dating Bronze Age/Iron Age transition sites and will encourage the application of archaeomagnetism to Bronze Age archaeology.

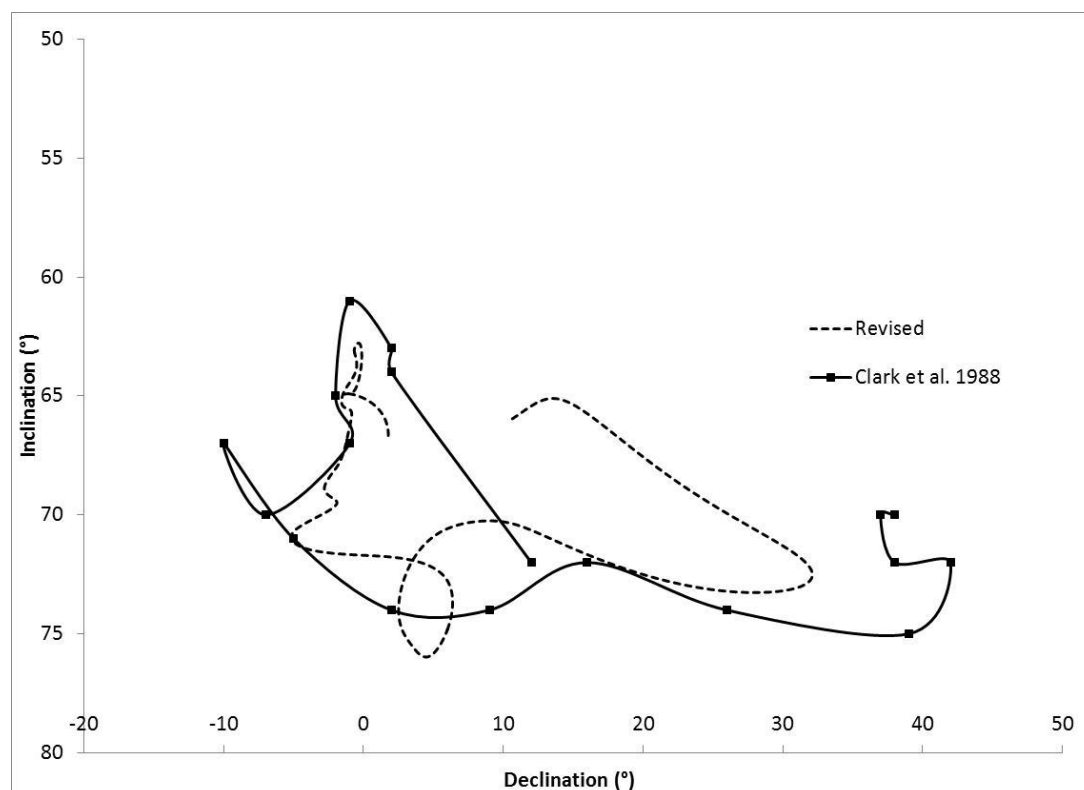


Figure 7.5: Bauer plot providing a comparison between the “Clark curve” (1988; solid line) that based the first millennium BC on lake sediment data and the preliminary version of the revised SVC (dashed line) where only archaeological data has been utilised.

## 7.6 Comparison with European secular variation curves

Britain is not the only European country to have an archaeomagnetic database; France, Bulgaria and Hungary also have a long tradition of archaeomagnetic studies. This situation has recently been changed by an international collaboration, the AARCH network (<http://dourbes.meteo.be/aarch.net/index.html>), which has generated a substantial body of archaeomagnetic data for the European continent. Over the past decade this has cumulated in the release of archaeomagnetic direction SVCs for ten other

countries worldwide. Of these, six regions have developed SVC for magnetic direction using the RenCurve algorithm: Austria (Schnepp & Lanos 2006), France (Gallet *et al.* 2002), Germany (Schnepp & Lanos 2005), Iberia (Gomez-Paccard *et al.* 2006), Italy (Tema *et al.* 2006) and the United Kingdom (Zananiri *et al.* 2007). Each of these SVCs contains the directional elements of the geomagnetic field and generally covers the last 3000 years (figure 7.6). The present day field for declination is changing at the same rate over western and middle Europe (Jackson *et al.* 2000) and the similarity between these six independently derived SVCs suggest that this trend continued back in time, an observation that had already been predicted (Lodge & Holmes 2009).

It will not be possible to make a full evaluation of the revised SVC until it is complete, yet it is possible at this stage to make some general comments relating to the overall success of this research project. The preliminary version of the revised British SVC (figure 7.4) shows higher amplitude and more frequent changes than all of the six published European SVCs (figure 7.6). Interestingly, the same general westward trend in declination peaking around 500BC then shifting easterly up to a peak around 1000BC, which is seen in all the European Bayesian SVCs, is repeated in the preliminary British SVC but the easterly peak in declination is twice the size. It is expected that after Bayesian modelling and MCMC sampling these peaks will become smoother, so less pronounced, but it is hoped that during this process most of the structure that is currently apparent is not lost, particularly for inclination (figure 7.4). Evidence from all European Bayesian SVCs had suggested that inclination remained relatively unchanged during the first millennium BC, although Western Europe showed a slightly steeper maximum inclination than central Europe, (figure 7.6). If this increase in structure remains after the modelling is complete, it will benefit the application of archaeomagnetism to dating, as it should enable smaller date ranges to be calculated. Overall, it would appear that the gross nature of geomagnetic secular variation remains unchanged but it is predicted that the changes made to the dataset during this research should enable the associated

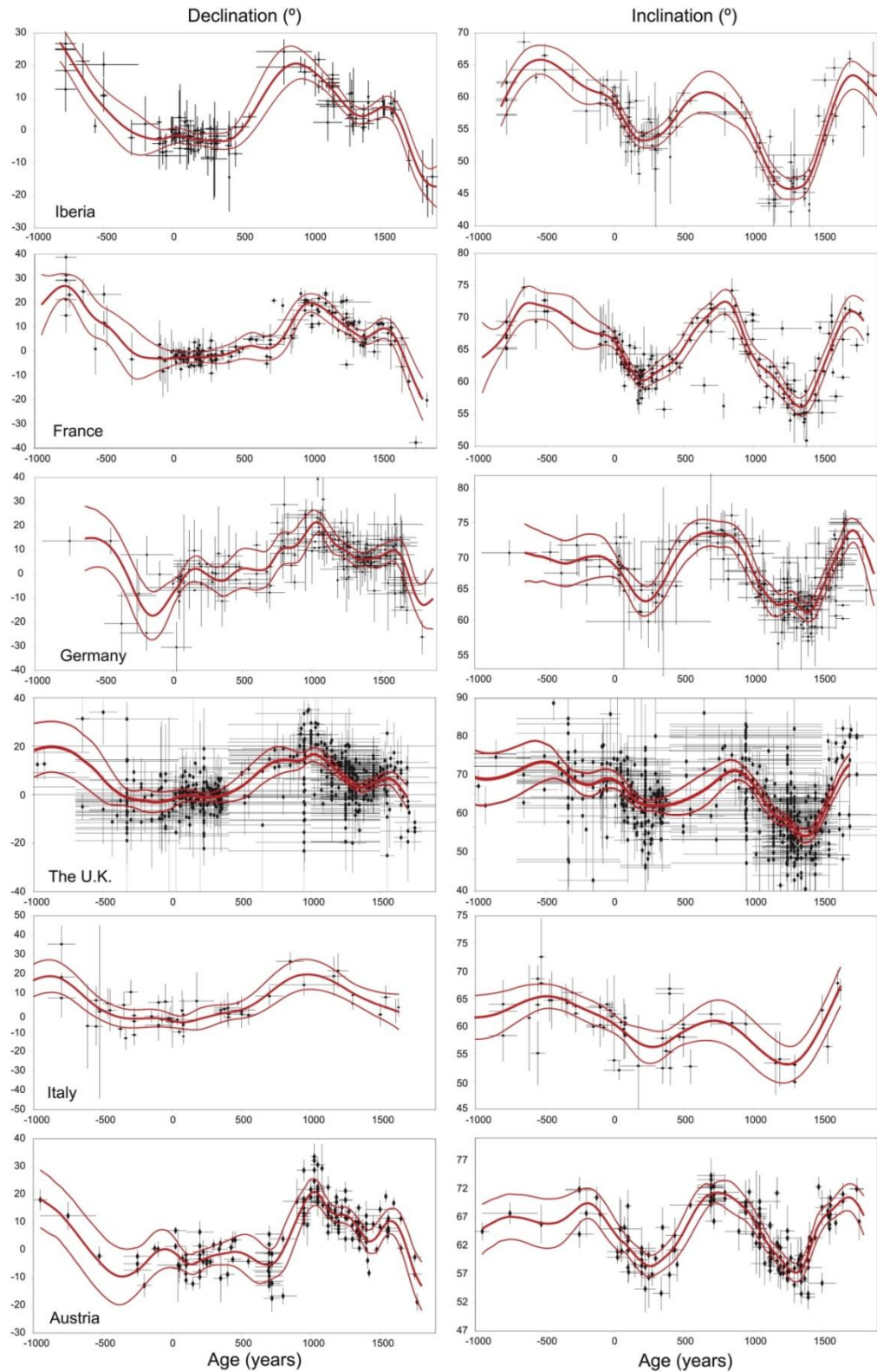


Figure 7.6: Comparison of all of the currently published directional European Bayesian SVCs (Pavón-Carrasco et al 2011: 411, figure 2). Thick red line represents the mean geomagnetic field element; thinner lines are uncertainties at 95% confidence level. The data used to construct the SVC, with associated errors, are shown in black. Note UK data and curve shown is Zananiri et al (2007) © Elsevier reproduced with permission.

error envelop for the revised British SVC to be reduced enabling the pattern of change to be resolved with greater precision.

## **7.7 Comparison with lake sediment data**

Given the results of the analyses in chapter 6, which suggested that TRM and DRM recorded the same direction over the same period of time, the presence of the pronounced peak in declination evident in the preliminary version of the British SVC was intriguing (section 7.4.5). Thus it was decided to compare the pattern of change from the preliminary SVC to that obtained from the British master curve (Turner & Thompson 1982) and FENNOSTACK (Snowball et al 2007) (figure 7.7). The consistency between these three records is striking, particularly when it is considered that the preliminary British SVC is composed entirely of magnetic data from archaeological sites. These graphs suggest that current lake records for the past 4000 years are comparable with the archaeological records, as peaks from the British archaeological SVC fall between those from the British lake master curve and FENNOSTACK. It is postulated that after Bayesian modelling the British archaeological SVC will more closely resemble the FENNOSTACK dataset. The dating will most likely remain unchanged when the British SVC is completed but it is suggested it is borne in mind that after 4000BP the curve is described by the information gathered from just three sites (section 4.7.3 and figure 7.3), the low density of data currently describing this section of the curve and will require inclusion of more Bronze Age sites. Yet that the same pattern of changes can be observed testifies to the importance of including weighting and the effectiveness of including stratigraphic information.

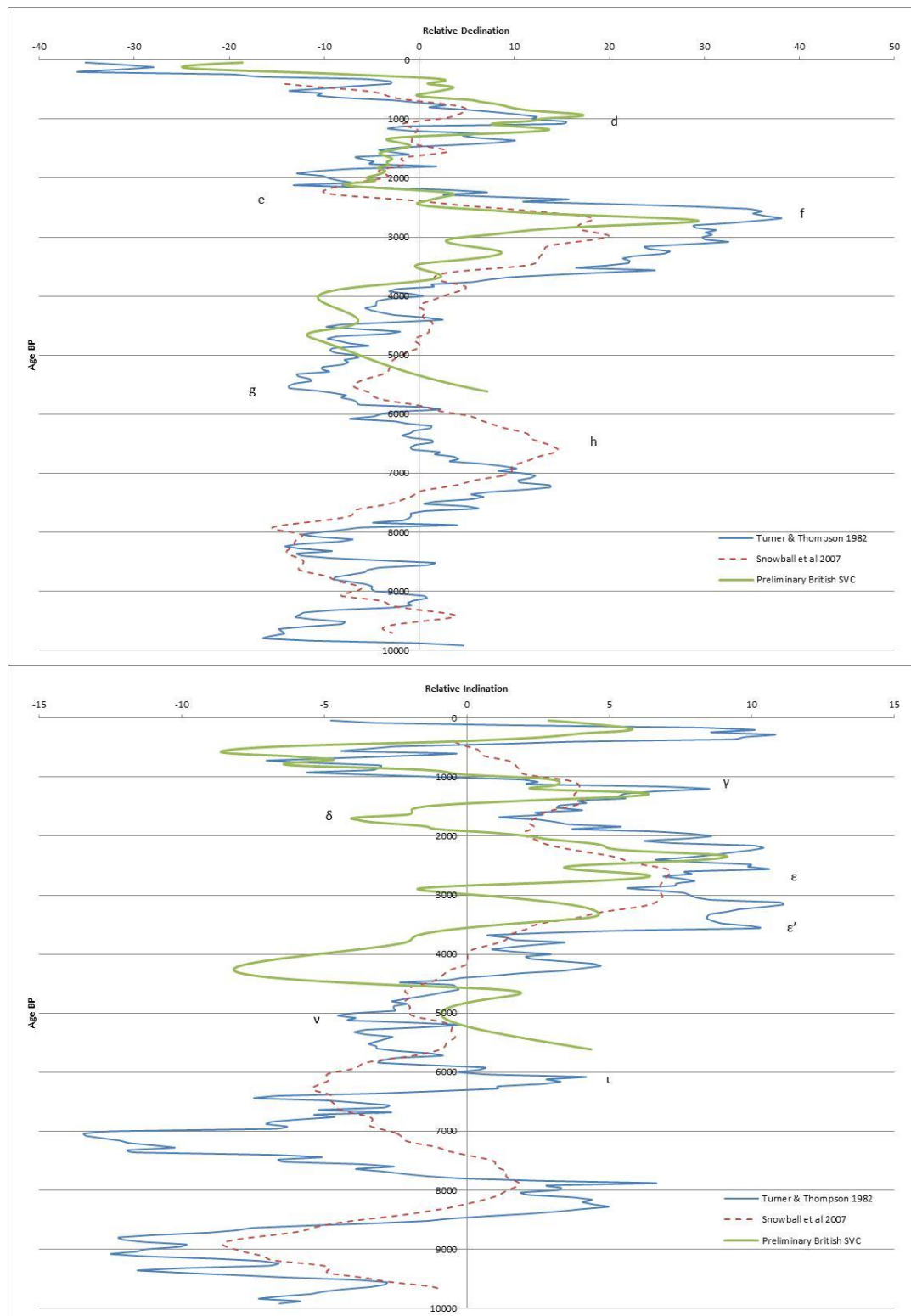


Figure 7.7: Graphs showing the relative pattern of secular variation in magnetic declination (top) and inclination (bottom) over time as described by the British master curve, FENNOSTACK (figure 6.7) and the preliminary version of the revised British SVC. Note how the same general patterning can be observed in each of these three independent records.



## 7.8 Summary

The preliminary version of the revised SVC for Britain presented in this section was produced by Philippe Lanos at l'Université de Rennes using the updated British database (appendices 1 and 4). This database resulted from the combined efforts of "Magnetic Moments in the Past" and this research project. The results presented in this chapter focused on the first millennium BC as this was the target period for this research and was where all the amendments and additions had been made. Any findings are based on these preliminary results, so may alter when the final curve is released. The changes made to the associated age estimates of the archaeomagnetic data appear to have had a significant impact on the first millennium section of the curve. It suggests that inclination experienced more changes during the first millennium BC than was previously anticipated. Declination is also marked by a rapid increase in less than two centuries, to the highest value recorded over the last 5000 years, followed by a general trend towards a gradual decrease with a small recovery around 300BC. When compared to the relative pattern of change displayed by both the British master curve and FENNOSTACK, the timing and amplitude of the maximum peak in declination is remarkably similar. Considering that all three records have been independently acquired, dated and produced, this does suggest that the similarities in the overall patterns from the signal archived by TRM and DRM are greater than the differences. It is also taken to suggest that the approach advocated in this research of focusing on the associated dating was both necessary and worthwhile. Furthermore the methodology employed has yielded positive results making the future of archaeomagnetic studies very promising.

## 8 Conclusions

André Previn: What were you playing just then?

Eric Morecombe: Grieg's Piano Concerto.

André Previn: You're playing all the wrong notes.

Eric Morecombe: I'm playing all the right notes – but not necessarily in the right order.

“Grieg's Piano Concerto.” The Morecombe and Wise Show (BBC) Christmas Special 1971

### 8.1 Research outcomes

This research hoped to contribute to current understanding of the past secular variation of the Earth's magnetic field (EMF). It focused on the first millennium BC, particularly on the evidence recovered from the archaeology of the British Iron Age. The overall aim was to use studies of the geomagnetic field, as recorded by archaeological and geological materials, to identify and characterise short timescale changes in the EMF. There has been a general consensus that the main weakness in archaeomagnetism lies with the chronological. This research has addressed this weakness, by focusing on the chronological data in the British archaeomagnetic dataset, and applying current archaeological understanding of the Iron Age period of British prehistory. The unique approach of this thesis required careful consideration of the nuances involved with estimating when past events on archaeological sites occurred. It also contemplated the level of precision that can be expected from the available information and the level of confidence that can be placed in it, so that these factors can be taken into account. This research also involved the collation of more data via literature reviews and a programme of fieldwork, and all data from archaeological sources were critiqued and re-evaluated in light of current archaeological understanding, by using a methodology designed to meet the specific requirements of archaeomagnetic data. In addition, the potential of other published archives of British geomagnetic data, specifically lake sediment data, was explored in some depth. The main outputs of this research are an updated database available at <http://www.brad.ac.uk/archaeomagnetism/> (and appendices 1-4), the foundation for a revised and extended secular variation curve and a potential methodology for combining archaeological and geomagnetic data.

The outcomes will be discussed in turn by referring back to the objectives laid out in chapter 1.

**Objective 1: an evaluation of published archaeomagnetic studies on Iron Age archaeology in Britain, with particular focus on 800BC - AD100.**

**Objective 2: the collation of currently unpublished magnetic data and allocating a chronological assignment to each magnetic direction so that it can be added to the British and global archaeomagnetic dataset and used to produce an updated British SVC.**

This research has focused on the first millennium BC, but in practice examined all the data points from the original dataset as published by Zananiri et al. (2007) whose median age was AD100 or earlier. This provided 115 magnetic directions. Of these, 103 magnetic directions now have revised age estimates, with only 12 having no change in their original age estimates. The decision to keep these unchanged was because either, it was not possible to confidently identify which excavation they were collected from (never mind locate the excavation reports) within the time constraints of this research, or there were difficulties confidently placing the heating event in the stratigraphic record (section 4.7). Extensive literature reviews and contact with other archaeomagnetic laboratories yielded a total of 117 new data points. It has been possible to obtain an estimate of age for all of these except 13. This was because the sites from which these 13 directions were collected are still being excavated or are currently being written up. Fieldwork and associated laboratory work undertaken as part of this research produced 25 new directions. It has been possible to obtain age estimates for three of these within the time frame of this project. Therefore, the total number of magnetic directions collated and examined for this thesis is 257. For reasons discussed in chapters 4 and 5, a total of 223 directions with revised age estimates were available to be included with the rest of the British archaeomagnetic data that could be used to create a future SVC for Britain. This has more than doubled the amount of data for this part of the British SVC. The original dataset, as published by Zananiri et al. (2007),

contained 620 archaeomagnetic directional data in total and, as it now contains 919 magnetic directions, this research has created a substantial increase of data in the British database.

The methods used, to assess the quality and reliability of each data point, were discussed in chapter 4. These predominately concentrated on highlighting the difficulties involved when attempting to obtain an estimate of when an event occurred; in this case the last time a heated feature cooled down. The results from applying this methodology demonstrate that identifying this event within the archaeological narrative of a site has a significant impact on the choice of date range applied to a magnetic direction. The temporal distribution of all the published data points evaluated now more accurately reflect the nature of the archaeological record from which they were obtained. Also, many data points from the original dataset now have more precise temporal resolution. This was because some of the subtle aspects of archaeological typology dating earlier workers had overlooked. Furthermore, it has also been possible to provide age estimates of  $\pm 200$  years or less for all of the new data points collated from Iron Age sites (figure 4.13). After the review, a much wider span of time is covered; this is due to the regional differences in Iron Age archaeology across Britain that had previously been overlooked. To conclude, this approach to revising the British SVC by re-assessing the data used to construct it has been successful and the dataset now displays a marked improvement both in quantity and quality. This means that a greater percentage of the data now fit some basic criteria that have been proposed for constructing reliable models.

**Objective 3: the collection of new magnetic data that will be incorporated into the British and global archaeomagnetic databases.**

There were two purposes behind undertaking fieldwork to collect more magnetic directions, to increase the number of archaeomagnetic data available for

this archaeological period and to raise the profile of archaeomagnetism as a dating method available to archaeologists. During the course of this research, it has been possible to obtain a total of 25 new magnetic directions and these were presented in chapter 5. This is despite the combined effects of the economic downturn in recent years, and the impending Olympic Games in London, which have resulted in a reduction in both the amount of development / infrastructure work undertaken, and the monies available for research excavations. Of these, only three magnetic directions obtained from fieldwork were associated with evidence which allowed an independent age to be assigned within the time frame of this research. The remaining directions have been included in the British database, and can be updated as the associated dating evidence becomes available. It is hoped that the tenure served as archaeomagnetic ambassador throughout this project yields positive results for future researchers.

**Objective 4: an investigation into the incorporation of magnetic data from British sedimentary sequences into the British archaeomagnetic SVC.**

Chapter 6 provided a detailed discussion on the merits and drawbacks of lake sediment data. The analysis of this data set was directed toward the application of dating evidence to this type of archive. The critique also found that the method used to combine sequences of magnetic data from lake cores needs to be more objective and rigorous before it can be incorporated into a SVC. However, it is possible to have confidence in the relative order of the geomagnetic secular variation recorded by lakes. It is concluded that the issue lies with determining the rate of the observed changes and retrieving absolute directions from sediment cores. Unfortunately, these aspects are also crucial for the inclusion of magnetic archives from lake sediments into an archaeomagnetic SVC. It is argued that the problem with lake data is not necessarily with the ability of lake sediments to capture secular variation but with our ability to confidently date these changes. Therefore, the main limitations are not necessarily related to how the ambient magnetic field is captured but incomplete stratigraphic knowledge; i.e. the rate of

sediment deposition and most importantly how this has changed over time. This is taken to suggest that if lake sediments had better chronological control these data could potentially be used in archaeomagnetic SVCs.

## **8.2 Further work**

Archaeomagnetic work on SVCs and global models of past changes in the geomagnetic field is a continuous process. It is anticipated that this research will form a significant contribution to future archaeomagnetic studies, including the application of archaeomagnetism to British archaeology and attempts to understand the nature of global geomagnetic changes to facilitate predictions on its future behaviour.

### **8.2.1 Short-term projects**

Along with the continued collection of new data, there are other aspects that warrant future research. In the short term, the directions from sites that were still being excavated should be followed up on and efforts to trace the excavation reports for those directions whose age estimates have not been revised should continue (sections 4.7 and 5.4 and appendix 1). Also, regarding SVC construction, this should involve a method to account fully for all the different types of probability distributions represented in the chronological data and to represent within the model the level of confidence attached to each form of dating evidence. Although it was possible to make some adjustments to the current version of RenCurve that allowed some weighting for the reliability of the dating evidence to be incorporated, it should be possible to develop a more appropriate and integrated method. It is also recommended that the rest of the database undergoes a similar treatment to the first millennium BC, as the rest of the British database would also benefit from refinement. In particular, the Saxon period and early medieval period would benefit from a review of the available dating evidence discussed further in section 8.2.2.

## 8.2.2 Longer-term projects

### *8.2.2i Lake sediment data*

All the evidence examined in chapter 6 suggests that the archive of secular variation within lake sediments does provide an accurate reflection of the actual changes experienced by the geomagnetic field through the Holocene. Therefore in theory, it should also match the general patterning that is emerging via the revised British SVC (figure 7.7), which was visible even with the raw archaeomagnetic data (figure 8.1). A potential avenue for further work would be to use lake sediment data to “fill in the gaps” left by the archaeological record. It is suggested that as it may be difficult to provide independent chronological control to these stratigraphic sequences, it could be possible to correlate them to the SVC as composed from archaeomagnetic directions. It is suggested that a pattern matching approach similar to that used in speech recognition software (O’Shaughnessy 2008, Benzeghiba et al. 2007) may provide useful avenues for this line of research. Alternatively, if a single fixed point in time (preferably more) could be identified in the lake sediment sequence, the relative changes in directions could then be matched to the patterning displayed in the archaeological SVC using correlation, so that the records reinforce each other. It is suggested that tephrochronology would make suitable tie points, but this would require the collection of fresh lake sediment cores. By employing recent innovations in sampling technique (Katari et al. 2000), it may be possible to recover evidence of the recent ash fall (Gudmundsson et al. 2010), which could in the future enable the sequences to be tied to observatory data. Furthermore, four tephra horizons have been identified in British sediments that were deposited during the period where there was potentially a rapid change in magnetic direction: GB4-150, Microlite, BMR-190 (Swindles et al. 2007) and Glen Garry (Barber et al. 2008), thus providing a useful check on this phenomenon.

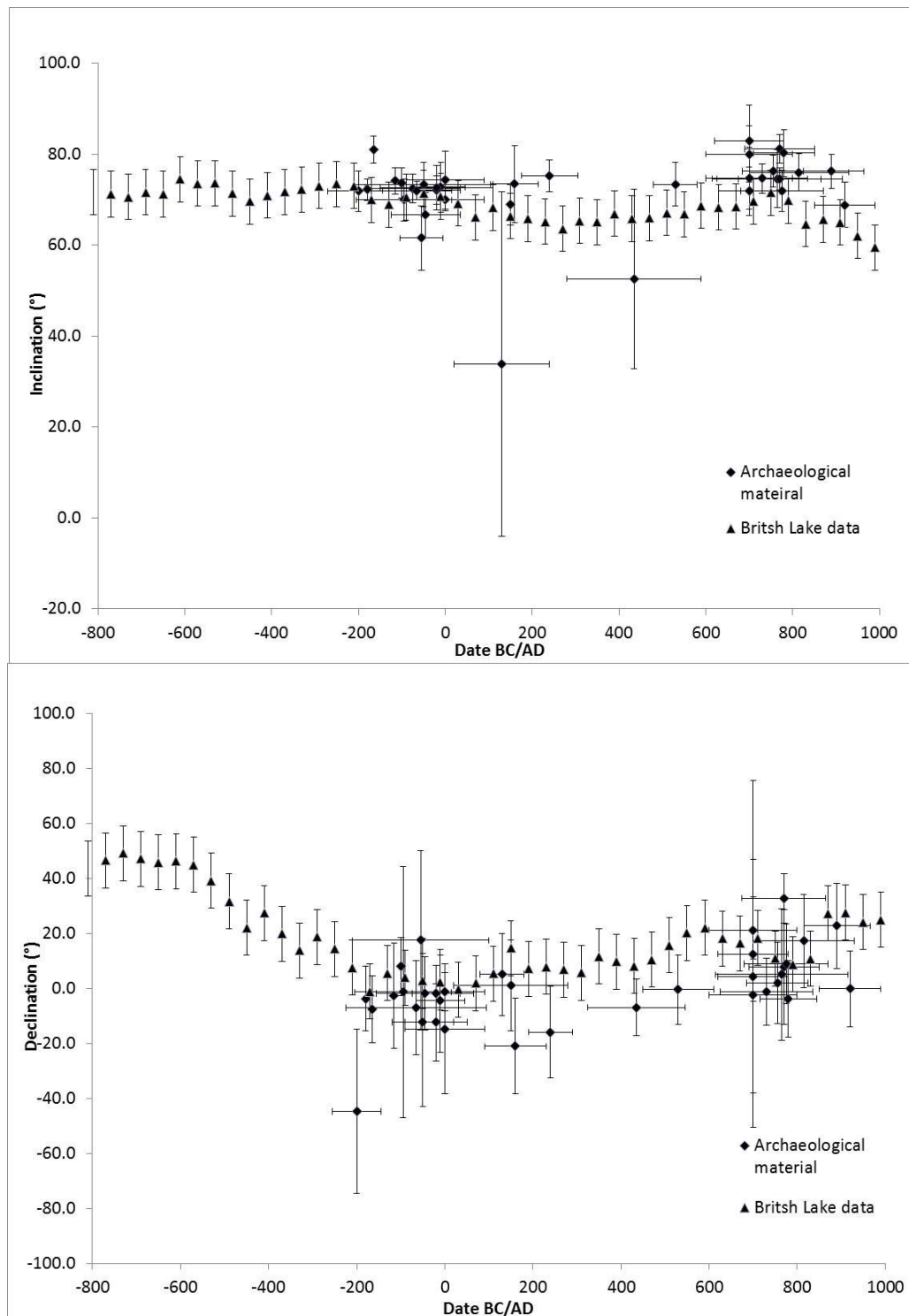


Figure 8.1: Two scatterplots showing how British lake sediment data could be used to “fill the gaps”; inclination versus time is at the top and declination versus time is shown in the bottom graph. The British master curve (Turner & Thompson 1981) is shown as triangles and the archaeomagnetic data with their revised date ranges are diamonds, all data have been relocated to Meriden ( $\gamma = 52.43^\circ$   $\lambda = -1.62^\circ$ ). For purposes of clarity a third of the archaeomagnetic data examined is shown, these data formed the “string” centred around 330BC (figure 7.1), but this should be sufficient to demonstrate that with a few exceptions both datasets appear to show the same general patterning, even with the current “preferred date ranges” for the lake dataset.



### *8.2.2ii Archaeomagnetic data*

The continued collection of archaeomagnetic data would only improve further editions of the British SVC, but there are three areas that would particularly benefit from further study. Firstly regarding the rest of the British database the next target period should be the latter first millennium AD or Anglo-Saxon period. The same problems identified with the dates allocated to the original Iron Age magnetic data apply to those data from the Anglo-Saxon period; the ages are typically AD700±300. This area of research may see a resurgence due to the discovery of the Staffordshire hoard in July 2009 (BBC news 2009), which consists of over 5kg of Anglo-Saxon gold, now housed at Birmingham Museum and Art Gallery. It is predicted that research on this hoard will peak over the next five years or so, which will eventually benefit a project similar in scope to this one but focusing on the early medieval period.

Secondly, there are remarkably few Scottish sites represented in the British database; out of the 436 sites in the British archaeomagnetic database, 16 are Scottish. Seven of these are vitrified hillforts (section 4.6.3); meaning that Scotland is currently covered by only 2% of the database and the location of these sites leaves most of mainland Scotland unrepresented. Therefore, this geographical area should be targeted for future archaeomagnetic studies, and vitrified hillforts could enable this to be realised as:

- large circuits of vitrified material survive above ground making access for sampling straightforward;
- as the material is vitrified any affects due to weathering should be less pronounced;
- only relatively small samples are needed from undisturbed material;
- sampling can be targeted and discrete so will not affect the integrity of the monument
- when the revised SVC is available it should be possible to obtain better calibrated archaeomagnetic dating than previous studies;

- a review is timely as it has been 20 years since the last comprehensive study on dating vitrified hillforts was undertaken.

This research could either focus on a specific area, such as Aberdeenshire, Fife or the Clyde valley, to examine the age distribution of vitrification events within a small region. Alternatively, a similar approach to Gentles' (1989) work could be taken, where monuments across a wide area of Scotland were sampled to see if vitrification was a contemporary phenomenon across Scotland, or if any patterns could be determined.

The third aspect is the collection of more data from Bronze Age sites. Although this research has extended the dataset, the resulting curve would not be well defined, particularly beyond 2000BC where it would only be constrained by data from three sites. It is necessary to address the low density of points, but it is hoped that there will be an "Ouroboros" effect, by extending the curve and enabling archaeomagnetism to be applied to Bronze Age archaeology will encourage its use. In turn, this should generate more Bronze Age magnetic data that can be used to estimate better quality SVCs in the future. The evidence from lake sequences suggests that there is a rapid shallowing in inclination during the Bronze Age making it a compelling feature to investigate further.

### **8.3 Concluding remarks**

The aim of this research was to use archaeomagnetic studies to identify and characterise short timescale changes in the EMF, focusing on the archaeology from the Iron Age period of British prehistory. Current errors in archaeomagnetism are dominated by errors associated with the estimate of age; this research has focused on the two aspects that can do most to improve the British SVC as estimated using the RenCurve software, reducing the associated age ranges and incorporating some weighting for the reliability of the applied dating evidence. The most obvious benefit of this re-evaluation is the increase in available data but the next British archaeomagnetic SVC may extend 2000 years further back, which would make

archaeomagnetic dating available to Bronze Age archaeology for the first time. By careful consideration of the formation processes that generate the archaeological record, this research has been able to refine the British archaeomagnetic dataset.

Preliminary results of the new SVC suggest that the geomagnetic field experienced more changes in direction than were previously known. The first millennium BC section appears to show more structure than previous SVCs and provides independent evidence that supports the rapid changes in magnetic direction during the first millennium BC suggested by geomagnetic data from lake sediments. The results of this research will contribute to the field of archaeology through more precise dating via archaeomagnetism, the inclusion of Bronze Age archaeology and may enable certain classes of archaeological artefacts to be considered in their own right and not be solely utilised as dating tools. A contribution has also been made to geomagnetism, as the refinements made to the data should enable our understanding on the nature of past geomagnetic secular variation to be taken forward. This should assist other scientists to make predictions on the future behaviour of the geomagnetic field and potentially enable higher harmonic contributions of the past geomagnetic field to be elucidated. So the future of archaeomagnetic studies looks bright, and it would appear that wherever magnetic north may have roamed during the past several millennia, a combination of science and archaeology will be able to retrace its path.

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